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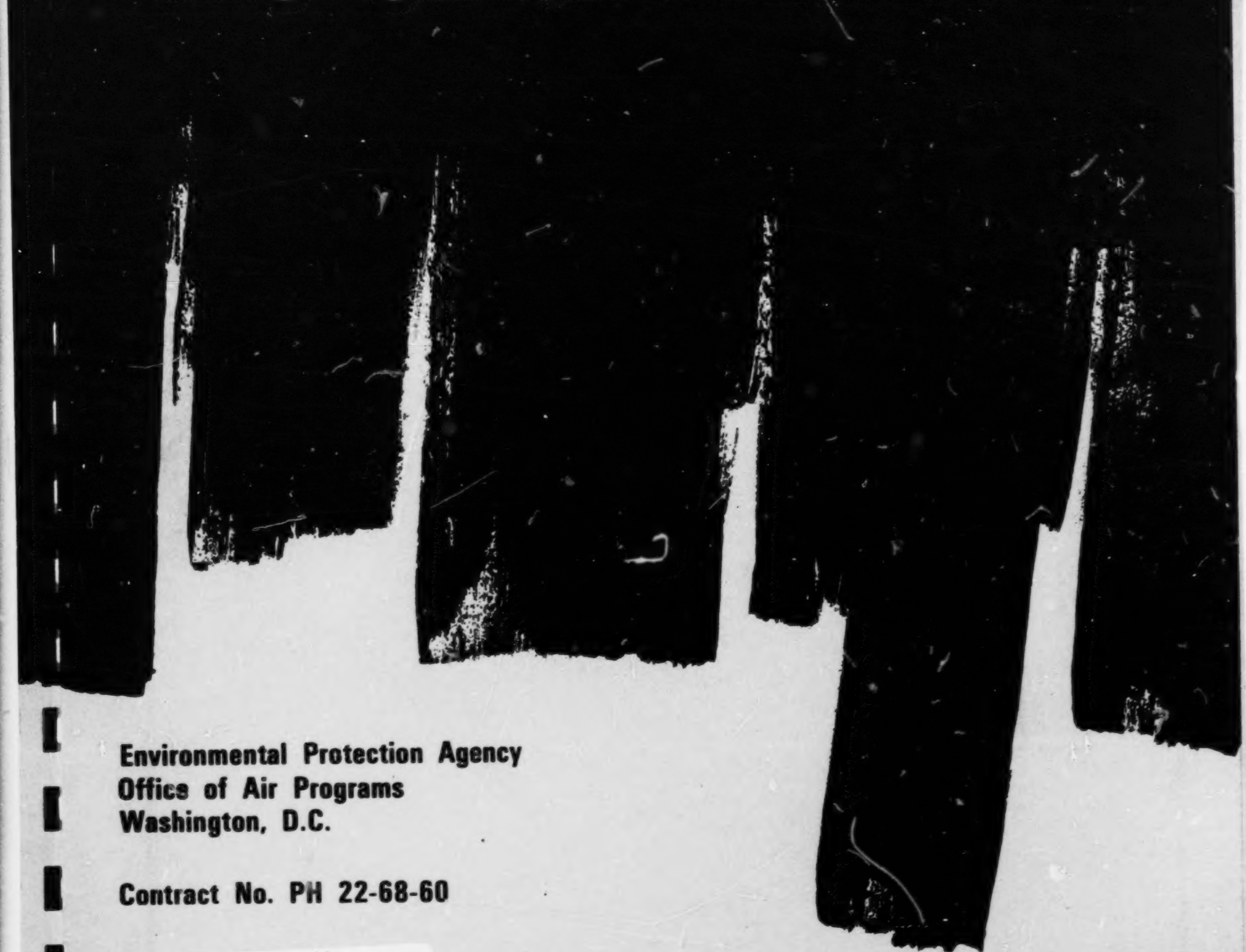
Sensitivity Analysis of Selected Air Quality Implementation Planning Program Input Parameters



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16. Abstracts

A major problem in the analysis of regional air pollution abatement (control) strategies is the collection and verification of an adequate data base. If computer programs (such as the Air Quality Implementation Planning Program (IPP)) are used, the scope of the data base must be expanded to include: (1) effective stack parameters and (2) regional cost data as an aid in the definition and use of these parameters, their sensitivity, with respect to pollutant concentration values and/or annual device cost are determined. The study utilizes the atmospheric diffusion model and the control cost model of the IPP (described in detail in Appendices A and B). Since these models use generally accepted techniques, and have been verified through extensive use, the study conclusions and recommendations are generally applicable. Chapter 2.0 presents the sensitivity analysis of the effective stack height parameters for individual sources. Chapter 3.0 presents the sensitivity analysis of the regional cost parameters with respect to the annual control cost of each physical device available in the IPP control cost model Chapter 4.0 presents a general summary of the parameter sensitivity results together with recommendations for the maximum variability of the parameters investigated.

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W. D. Dickerson

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1.0 INTRODUCTION

A major problem in the analysis of regional air pollution abatement (control) strategies is the collection and verification of an adequate data base. If computer programs (such as the Air Quality Implementation Planning Program [IPP 1970]) are used, the scope of the data base must be expanded to include: (1) effective stack parameters* (stack height, exit velocity, exit diameter, and exit temperature) and (2) regional cost data (interest rate, utility costs, labor rates, and fuel costs). In practice these data are often difficult to define; the effective stack parameters because of the physical measurements involved and the cost parameters because regionwide average values, suitable for all sources, must be found.

As an aid in the definition and use of these parameters, their sensitivity, with respect to pollutant concentration values and/or annual device cost are determined. The study utilizes the atmospheric diffusion model and the control cost model of the IPP (described in detail in Appendices A and B). Since these models use generally accepted techniques, and have been verified through extensive use, the study conclusions and recommendations are generally applicable. The study results are presented such that: (1) the accuracy requirement of each parameter can be determined as a function of the remaining parameters and a maximum allowable pollutant concentration and/or annual control cost error, and (2) given the complete set of parameters and parameter accuracy estimates, the resulting maximum possible error in pollutant concentration and/or annual control cost can be estimated.

Chapter 2.0 presents the sensitivity analysis of the effective stack height parameters for individual sources. The source parameter sensitivity is determined with respect to the maximum annual average pollutant concentration value (χ_m) produced by a given source. A general formulation for the variation of χ_m as a function of the uncertainty in any one or all of the effective stack parameters is obtained. The formulation is then used to determine the parameter sensitivity for several source category-size combinations. The parameter values used in the analysis are derived from a survey of 5 detailed emission inventories (Appendix C).

To page 2

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* The term parameter is used here to denote inventoried (i.e., input) data whereas the term variable denotes calculated (i.e., output) data.

From page 1

A Chapter 3.0 presents the sensitivity analysis of the regional cost parameters with respect to the annual control cost of each physical device available in the IPP control cost model. This general analysis does not include fuel substitution measures since these are highly dependent on existing source configuration and user input sulfur limitations. Annual control cost equations are summarized for each device (subject to the preset data assumptions of the model). The sensitivity of the annual cost for each device with respect to interest rate, labor rate, electricity cost, water cost, and natural gas cost, is then determined for a range of plant sizes.

Chapter 4.0 presents a general summary of the parameter sensitivity results together with recommendations for the maximum variability of the parameters investigated.

This study has shown that relating parameter uncertainty to variable error on a per-source basis is a valid approach as an aid in the determination and use of the effective stack parameters and regional cost data. In view of this, it is recommended that; (1) in studies in which average parameters are determined (existing data summaries, literature searches, etc.), the parameter uncertainty be related to variable error as a measure of the average parameter validity, and (2) an extension of the cost sensitivity study be made to include the preset data within the cost equations (purchase cost parameters, labor quantity required per device, etc.) and the fuel substitution measures. The last item is particularly important since these measures are the major SO_2 control methods.

2.0 PARAMETER SENSITIVITY WITH RESPECT TO MAXIMUM POLLUTANT CONCENTRATION

In this chapter those point source emission inventory stack parameters used by the IPP diffusion model are analyzed to determine their sensitivity with respect to maximum long term pollutant concentration values. Since this study is for individual source parameters, the maximum pollutant concentration values are for a single source and not the region wide maximum concentration value. This measure of the parameter sensitivity was chosen because it is the variable most sensitive to input parameter changes. In addition, the maximum concentration value provides the best single indication of the impact of a given source on the regional air quality.

The complete set of input data required by the model, summarized in Table 2-1, consists of the emission inventory data and the meteorological data. Since the meteorological data are, in general, region dependent, a nominal set was selected for this study. The determination of this nominal set was done as follows:

- Stability Wind Rose - As described in Appendix A, the stability wind rose gives the relative frequency of occurrence of each combination of the 16 wind speed directions, 6 wind speed categories and 5 stability categories. For the study of point source parameters, however, only a single wind direction is required. To determine a nominal set of data, average stability-speed data was obtained from the stability wind roses used in the Chicago, Cincinnati, Denver, St. Louis, and Washington regions. This was accomplished by averaging the wind speed distribution for each wind speed direction-stability combination.
- Mixing Height - For the range of parameters considered in this study, downwind distances to the maximum concentration point do not exceed 10 kilometers. For such travel distances, the mixing heights above 500-600 meters do not effect the maximum concentration value. Since the normal range of average afternoon mixing heights is from 700 to 2,000 meters, a value of 1,000 meters was artibrarily picked for this study (check runs with a mixing height of 500 meters and large effective stack

Table 2-1. Diffusion Model Input Parameters

Parameter	Symbol	Units
Meteorological Parameters		
Stability Wind Rose--Relative frequency of occurrence for each combination of the standardized 16 wind directions, 6 wind speed classes and 5 stability classes	-	-
Mixing Height--Height above surface through which the pollutant is mixed.	L	Meters
Ambient Pressure	P	Millibars
Ambient Temperature	T_a	Degrees Kelvin
Pollutant Decay Factor--Time, after release, at which pollutant concentration has decayed to one-half its original value.	λ	Hours
Emission Inventory Parameters		
Stack height	h	Meters
Exit Velocity	V	Meters/second
Exit Diameter	D	Meters
Exit Temperature	T	Degrees Kelvin

heights indicate less than 2% error occurs in the maximum concentration). The reader should note, however, that the mixing height value can effect air quality on a regionwide scale. This is caused by pollutant travel distances large enough to allow vertical dispersion interference at the mixing height.

- Ambient Temperature and Pressure - The normal ranges of the ambient temperature and pressure are: 270 to 300 degrees Kelvin and 950 to 1,050 millibars, respectively. Since these parameters are used explicitly in the effective stack height calculation, their sensitivity with respect to maximum concentration will also be determined. The nominal values used for these parameters are 288° Kelvin and 1,000 millibars.
- Pollutant Decay Factor - Although this parameter can have a pronounced effect on regionwide air quality, the commonly used pollutant decay factors of three hours or greater have very little effect on maximum concentration values (less than 1% for the parameters used in this study). This is due to the short travel distance (and therefore travel time) to the maximum concentration point. For this study, then, an infinite pollutant half-life value was used.

The effective stack height (H), defined by Equation (1) is composed of the physical stack height and the plume rise (which accounts for the buoyancy and vertical momentum of the effluent).

This formulation, due to Holland, is used in the IPP Diffusion Model.

$$H = h + \Delta h = h + \frac{VD}{U} (1.5 + 2.68\ E\text{-}3PD(1 - T_a/T) \qquad (1)$$

where

h = stack height

ΔH = plume rise (meters)

V = exit velocity (meters/second)

D = exit diameter (meters)

T = exit temperature (degrees Kelvin)

P = ambient pressure (millibars)

T_a = ambient temperature (degrees Kelvin)

U = average wind speed (meters/second)

The analysis procedure was to first establish a relationship between the maximum concentration (χ_m) and the effective height of release (H). Then the variations in H (and therefore χ_m) with respect to the parameters defined in Equation (1) were determined. To establish the χ_m versus H relationship, a series of runs were made varying h from 20 to 150 meters and UΔh (normalized plume rise) from 30 to 750 meters. Figure 2-1 shows the results of these runs in terms of the normalized maximum concentration (maximum concentration divided by the emission rate in tons/day).

In order to calculate an effective stack height from this data, an appropriate value of U was required. Although somewhat arbitrary, this value should reflect average conditions in order to produce realistic effective stack height values. An average value of 4.5 meters/sec. was obtained from the stability-speed profile used, by averaging over all stability-speed combinations. Then, combining the stack height and normalized plume rise values into effective stack height values lead to the desired maximum concentration versus effective stack height curve shown in Figure 2-2. Applying a curve to fit to the data in Figure 2-2 yields the relationship:

$$\chi_m/Q = BH^{-A};\ A = 2.562,\ B = 47\cdot10^6,\ Q = \text{emission rate (tons/day)} \quad (2)$$

This figure also presents the downwind distance at which the maximum concentration occurs. The "fan" at the high H end of the distance curve indicates that, for large effective stack heights, there exists an area of maximum concentration as opposed to a single point. Although the distance curve is not required in the analysis of this chapter , it does provide useful data for locating the χ_m point for a given source. Using this curve to get distances and the regional stability wind-rose to determine the most active wind direction radial should provide the χ_m location for each source.

As a check on the validity of the results in Figure 2-2, a set of χ_m/Q versus H data was obtained by making a series of runs using the most active wind direction stability-speed values from the Washington, D. C., Cincinnati, Philadelphia and St. Louis regions. A plot of these data is shown in Figure 2-3. No regional calibration values were used in these runs. Note that the slopes of the "actual" and average curves are the same. This is the key factor in this study since changes and not absolute magnitudes are being considered.

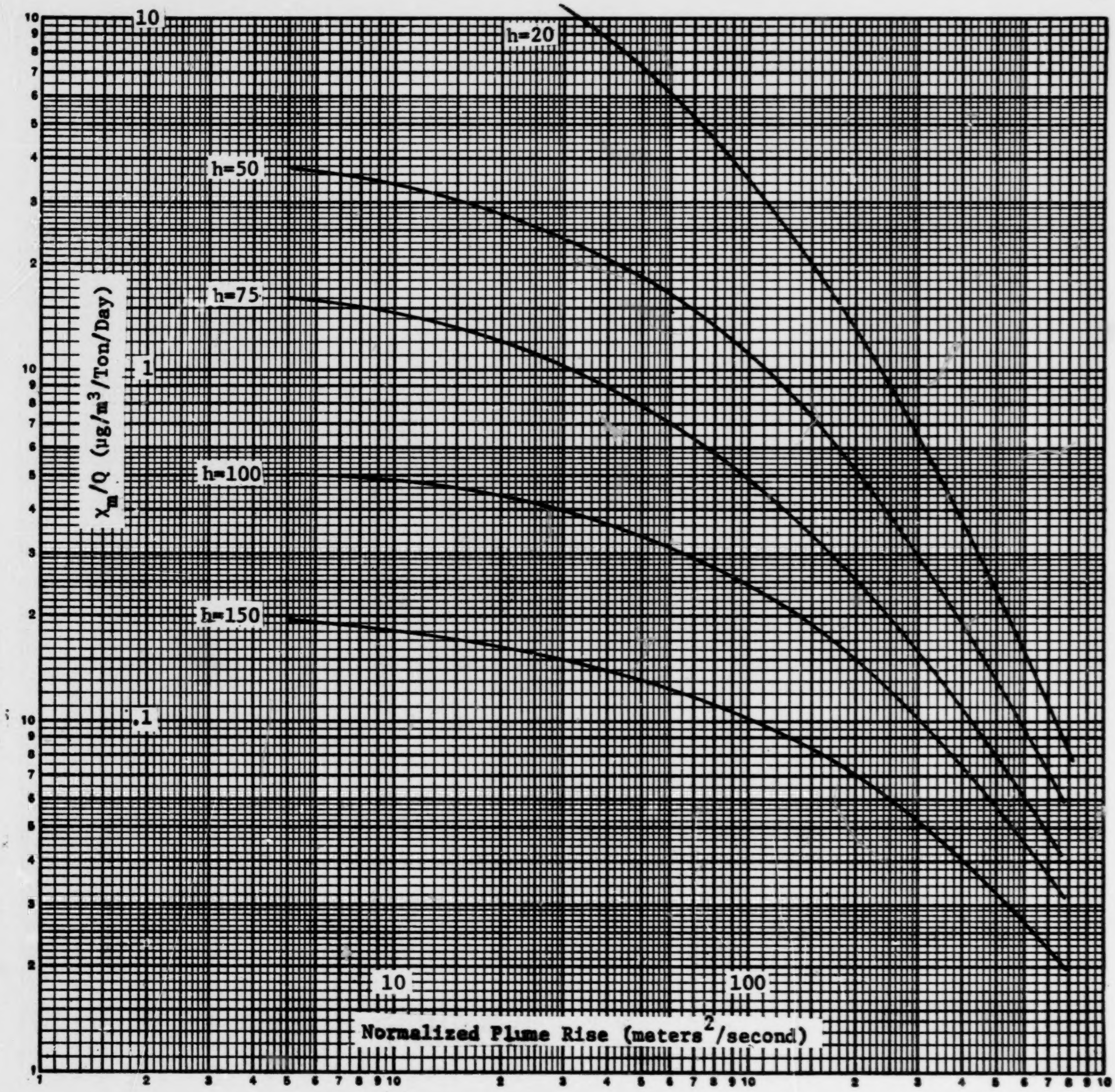

Figure 2-1. Maximum Concentration Variation With Normalized Plume Rise

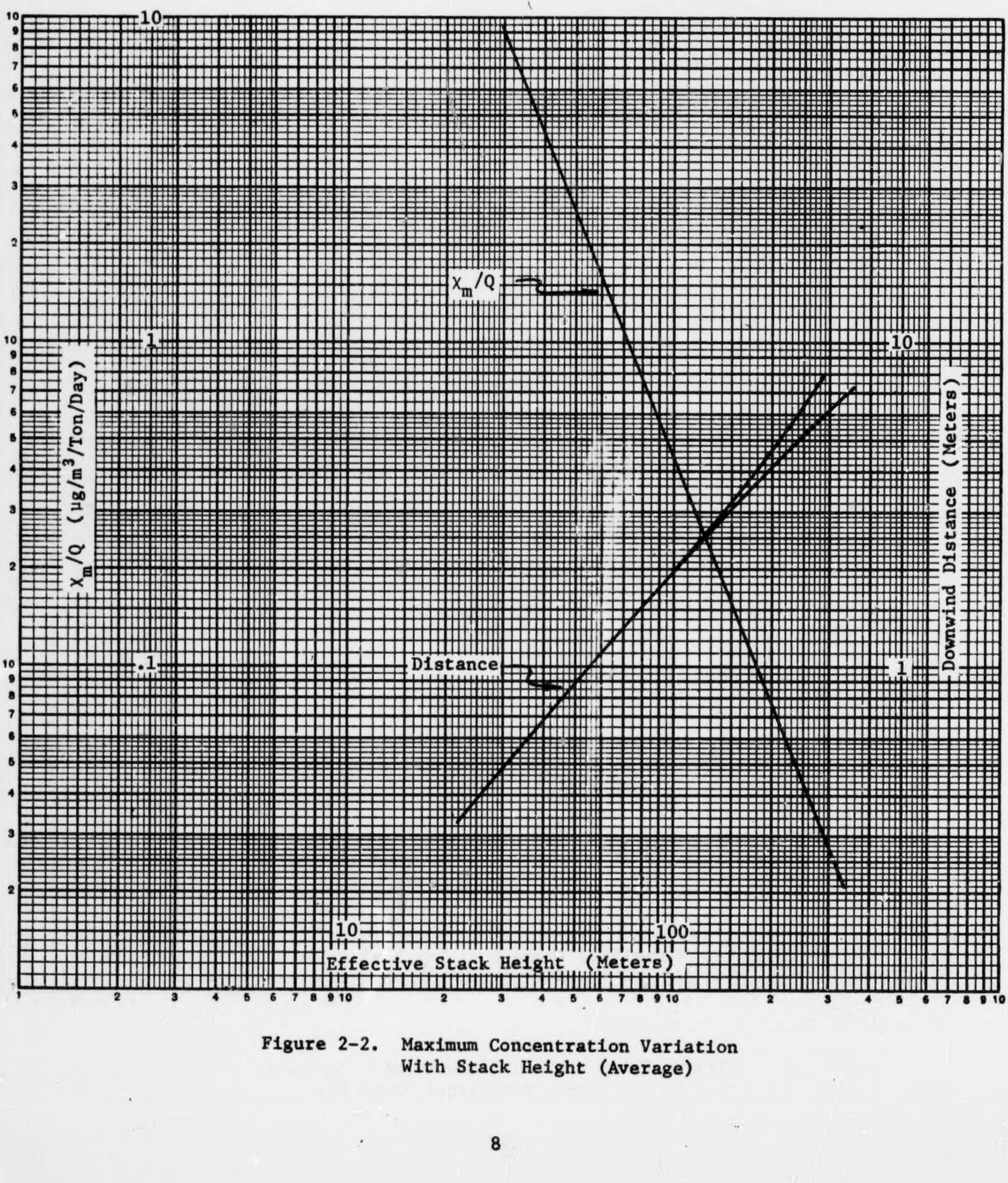

Figure 2-2. Maximum Concentration Variation With Stack Height (Average)

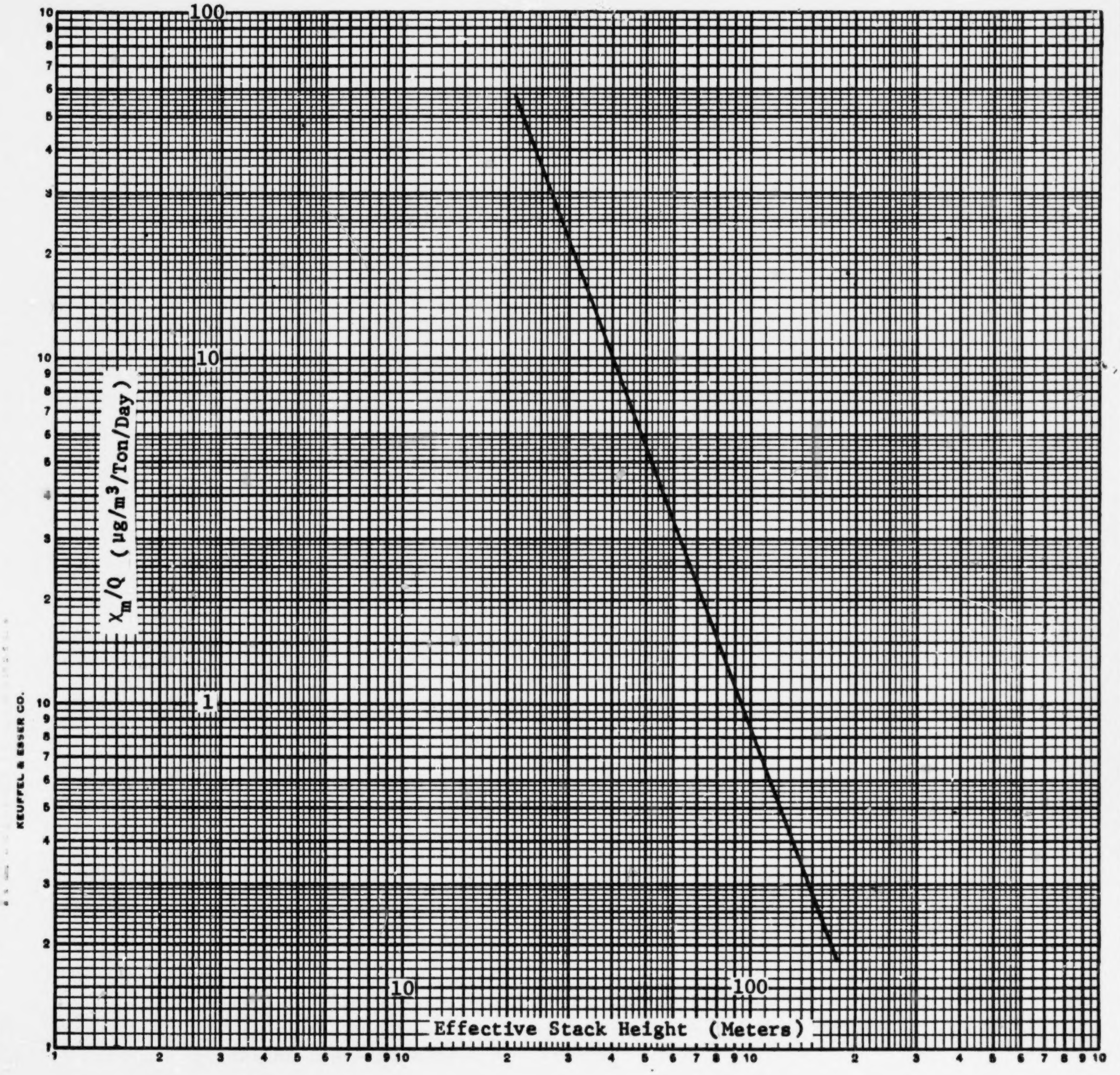

Figure 2-3. Maximum Concentration Variation With Effective Stack Height (Regional).

The sensitivity of the effective stack height with respect to changes in χ_m is obtained from Equation (2) as

$$\chi_m/\chi_{m_o} = (H/H_o)^{-A} \tag{3}$$

Figure 2-4 shows this relationship for a range of H/H_o from .2 (-80%) to 4 (+400% change in H). The use of ratios is used throughout this section and has the advantage of producing a direct variation in χ_m with respect to a given variation in H. For example, if the effective stack height is assumed to be 200 meters ± 10 meters, (possible error of 10%), Figure 2-4 [or Equation (3)] shows that χ_m will, at most, be in error by 25% (corresponding to $H/H_o = 190/210 = .905$).

To relate the effective stack height parameters to the height ratio, Equation (1) is used. As an example, the variation of H/H_o with respect to a new exit temperature (T_1) is given by

$$\frac{H}{H_o} = \frac{h + \frac{VD}{4.5} \quad [1.5 \ + 2.68E\text{-}3PD(1-T_a/T_1)]}{h + \frac{VD}{4.5} \quad [1.5 + 2.68E\text{-}3PD(1-T_a/T)]} \tag{4}$$

Obviously, the height ratio is dependent on both the variation of the parameter under consideration and the nominal values chosen for all of the parameters. To illustrate, the variation of a typical set of stack parameters (Table 2-2) is calculated. Using this data and Equations (3) and (4), the sensitivity of each parameter is obtained. Table 2-3 summarizes the parameter sensitivities for several parameter accuracy values.

The maximum possible error in χ_m for this example can also be calculated if the accuracy limits of each of the parameters is known. This is accomplished by using the maximum and minimum parameter values to determine the minimum value of H/H_o (and thus the maximum value of χ_m/χ_{m_o}). As an example, assume that all of the parameters in Table 2-2 have an accuracy limit of ± 10%. Then,

$$\text{minimum } (H/H_o) = \frac{72 + \frac{18*3.6}{4.5} [1.5 + 2.68*.99*3.6(1-291/455)]}{88 + \frac{22*4.4}{4.5} [1.5 + 2.68*1.01*4.4(1-285/465)]}$$

$$= \frac{143.1}{220} \quad = \ .65$$

Now, from Figure 2-4, $\chi_m/\chi_m = 2.9$. Thus a 20% accuracy limit for all

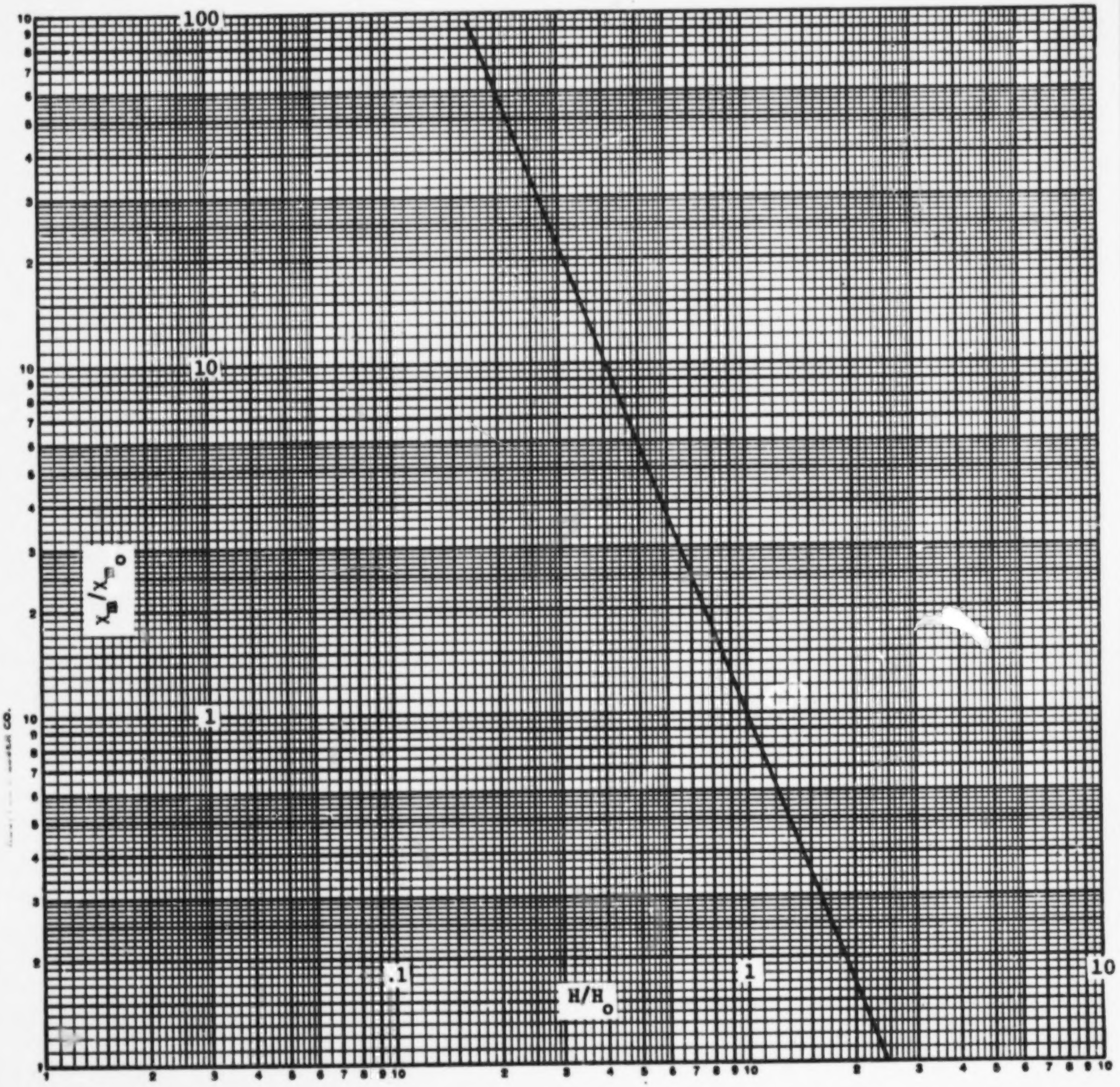

Figure 2-4. Maximum Concentration Ratio Variation With Effective Stack Height Ratio

Table 2-2. Effective Stack Height Parameters For Example Case.

Parameter	Value
Stack Height (h)--Meters	80.
Exit Velocity (V)--Meters/second	20.
Exit Diameter (D)--Meters	4.
Exit Temperature (T)--°K	460.
Ambient Pressure (P)--mb	1000.
Ambient Temperature(T_a)--°K	288.

Table 2-3. Summary of Parameter Sensitivity For Example Case.

Parameter	Maximum Possible Error in χ_m(%) Parameter Error=10%	=20%	=50%
h	12.	25.	90.
V	10.	21.	120.
D	20.	75.	300.
T	25.	65.	*
P	10.	27.	*
T_a	20.	40.	*

*Exceeds parameter range.

of the stack parameters results in a maximum possible error in χ_m of almost 200%. It should be noted that the "maximum possible error" value is quite conservative since it assumes that all of the parameter values are underestimated (or overestimated) by the maximum variation.

To develop the sensitivity of the effective stack height parameters in general, nominal parameter data sets applicable to various size powerplants, fuel combustion sources (except powerplants) and industrial process sources were utilized. These data, shown in Table 2-4, were obtained from a survey of 6 detailed emission inventories (see Appendix C).

Table 2-5 shows the individual parameter deviation (from the nominal) required to produce a 5% deviation in χ_m. In general, these results show that the exit diameter and temperature are the most sensitive. The maximum possible error in χ_m for all cases is less than 50%. This suggests that the set of parameter errors in Table 2-5 could be used as a guide for determining inventoried parameter requirements. Averaging the lowest deviation values in each category results in the suggested parameter limits shown in Table 2-6.

Table 2-4. Nominal Effective Stack Height Parameter Values.

			Parameter Values		
		Plant Size =	Small	Medium	Large	Extra-Large
		Rated Capacity (BTU/hr)[1] =	$50 \cdot 10^6$	$400 \cdot 10^6$	$1500 \cdot 10^6$	$6000 \cdot 10^6$
		ACFM =	$20 \cdot 10^3$	$150 \cdot 10^3$	$600 \cdot 10^3$	$2000 \cdot 10^3$
Parameter						
h(meters)	PP[2]		-	64.	83.	122.
	FC		41.	47.	51.	55.
	IP		18.	35.	65.	91.
V(meters/sec)	PP		-	7.	12.	22.
	FC		5.	9.5	13.5	17.5
	IP		6.	6.	6.	6.
D(meters)	PP		-	3.5	4.	5.5
	FC		2.	2.5	3.	3.5
	IP		2.	4.5	6.	7.5
T(deg.Kelvin)	PP		-	465.	440.	425.
	FC		525.	485.	460.	435.
	IP		500.	425.	375.	300.
H_o(meters)[3]	PP		-	92.	139.	290.
	IP		50.	69.	92.	119.
	FC		28.	67.	107.	114.

---

[1] Defines plant size.

[2] PP = Powerplants, FC = Non-Powerplant Fuel Combustion, IP = Industrial Process

[3] Calculated using nominal data in Equation (1).

Table 2-5. Percent Parameter Change Required to Produce a 5 Percent χ_m Change.

Paremeter		Parameter Change (%)			
		Small Plant	Medium Plant	Large Plant	Extra Large Plant
H(meters)	PP*	-	3.7	3.0	4.3
	FC	2.1	3.8	3.3	4.1
	IP	2.9	3.6	2.9	2.2
V(meters/sec)	PP	-	6.0	4.6	3.4
	FC	11.4	6.2	4.1	4.7
	IP	5.0	3.9	4.5	9.2
D(meters)	PP	-	3.7	2.5	2.3
	FC	6.5	3.5	2.7	2.0
	IP	3.5	2.2	2.5	8.5
T(deg.Kelvin)	PP	-	3.2	3.2	2.1
	FC	12.0	5.7	1.0	2.6
	IP	6.4	2.0	1.8	1.0
P(millibars)	PP	-	8.2	6.0	4.3
	FC	16.5	9.2	6.7	5.2
	IP	19.2	5.3	6.4	26.0
T_a(deg.Kelvin)	PP	-	3.1	3.1	2.1
	FC	13.5	6.1	3.5	2.8
	IP	6.8	2.5	2.1	1.0

---

[*] PP = Powerplant, FC = Non Powerplant Fuel Combustion, IP = Industrial Process.

Table 2-6. Suggested Maximum Value Range for Effective Stack Height Parameters.

Parameter	Value Range
h(meters)	± 3%
V(meter/sec)	± 5%
D(meters)	± 3%
T(deg. Kelvin)	± 3%
P_a(millibars)	± 5%
T_a(deg. Kelvin)	± 3%

3.0 PARAMETER SENSITIVITY WITH RESPECT TO DEVICE ANNUAL CONTROL COST

In this study, an investigation is made of the sensitivity of the regional cost parameters with respect to the annual cost of the various control devices specified in the Implementation Planning Program. Table 3-1 gives a description of the regional cost parameters and other data required in the control cost equations. The devices available within the IPP are described in Table 3-2. The IPP control cost formulation, as described in Appendix B, together with the preset data used in the model (Table 3-3) are used as the basis for the parameter sensitivity determination.

The annual cost for each control device is composed of the total installed cost and the operating and maintenance cost (O&M). The total installed cost includes the purchase cost, installation cost, and interest charges. In general, the O&M costs consist of: (1) the electrical power cost necessary to maintain the effluent gas flow through the control device, (2) the cost of water, chemical, and natural gas used by the device, (3) the cost (or credit) resulting from disposal of the collected pollutant, and (4) the labor cost associated with device maintenance. The O&M costs for each device is composed of various combinations of the general O&M formulation. The specific equations used to determine the annual control cost for each device are summarized in Table 3-4. Subject to one approximation, these equations were taken directly from Appendix B. The exception is the way in which the annualized capital charge is calculated. This calculation utilizes a Capital Recovery Factor (C.R.F.) calculated as

$$\text{C.R.F.} = \frac{i(1+i)^N}{(1+i)^M - 1}$$

where i is interest rate and N is the rated life of the device. Since the rated life (N) of the devices considered is between 15 and 20 years, the C.R.F. can be approximated by a straight line, for an interest range of 5 to 10%, to within 1/2% of the exact value. This approximation allows easy manipulation of the capital charge terms.

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Table 3-1.
Control Cost Input Parameters

Regional Cost Input Parameters

Labor Cost Rate (C_ℓ, \$/hr)

This is the average hourly wage rate for unskilled labor within the region. Although the quantity of labor required depends on the characteristics of the emission source and the control device applied, the labor cost rate is determined only by the regional labor market.

Interest Rate (C_i, %)

The prevailing interest rate. This item is used in computing an annual cost based on the purchase and installation costs of control devices.

Utility Costs

The cost of electricity (C_e, \$/kwhr), natural gas (C_g, \$/cu.ft.), and water (C_w, \$/gallon). Separate electricty and natural gas cost values may be input for power plants (SIC 4911), industry (SIC 3XXX and 2XXX), and commercial (all other SIC numbers).

Control Cost Preset Parameters

Price Coefficients

The cost of each control measure to a particular source is determined by multiplying some measure of the source size by input price coefficients. Usually the measure of size is the number of cubic feet of gas per minute to be treated (ACFM). For some devices, however, the power-generating capacity, fuel usage, or some other measure is used. The price coefficients for most devices were taken from the Control Techniques Documents for Particulates and Sulfur Oxides prepared by the National Air Pollution Control Administration.

Table 3-1. (Continued)

Installation Cost Factor

This factor is used in determining the total cost of installing a control device on a particular pollution source. It accounts for those cost elements which depend on the characteristics of the source and of the device itself. The installation cost factor includes the costs of transportation, erection, architectural and engineering, auxiliary equipment, utility connection, startup, spare parts, and land and buildings. For each control device preset in the program, a corresponding installation cost factor, which represents a fraction of the total purchase price, is also preset. The preset factors are those presented in the 1960 NAPCA document, Control Techniques for Particulates.

Expected Life (years)

The length of service expected from each control device is included in each device record. This item is used to apportion the total installed cost of the control device into an annual charge value.

Labor Quantity (hrs/year)

This is the yearly amount of labor necessary to operate and maintain each device. Labor quantities associated with four different plant sizes are required. The appropriate value for each particular emission source is selected and applied by the Control Cost Program. The total labor expense, which is one of the major components of device operating and maintenance costs, is calculated as the product of the quantity of labor and the labor cost rate. Labor quantity is computed by converting skilled and supervisory hours into equivalent unskilled hours.

Operating Cost Factors

A number of factors relating to each device are considered in the computation of operating cost. The pressure drop (in. H_2O) associated with each device is a function of the resistance to gas flow through the device and therefore provides a measure of the amount of power necessary

Table 3-1. (Continued)

to operate it. Chemical costs ($/ton) give the relative costs of additives used in wet scrubbing when gases in the effluent stream are used, a fuel factor must be included. This factor corrects the computed fuel usage to account for the various heat input requirements (see Particulate Control Techniques Document).

Disposal Cost or Credit ($/ton)

For each pollutant collected, there must be a charge for its disposal. This charge is associated with the control device, since the form in which the pollutant is collected is quite important. If the collected pollutant has value, either directly or by return to a process, then the disposal charge will be negative relative to the other device costs.

Rated Efficiency (%)

These data elements represent the basic removal efficiencies of the control device under consideration for the various pollutants. These efficiencies are modified within the Control Cost Program to reflect variations in source characteristics. The modifications are made on the basis of preprogrammed engineering criteria which take into consideration the effect of existing control devices.

Emission Inventory Parameters

Effluent Gas Stream

The type and size of control devices applicable to a source are strongly affected by the two gas stream parameters: maximum exhaust gas volume (ACFM) and stack exit temperature (T, degrees Kelvin). For example, considerably more expensive fabric-filter installations are required when high-temperature gas must be cleaned.

Existing Pollution Controls (n, %)

The efficiency of existing air pollution control devices. When adding new control devices, they must be compatible with existing equipment,

Table 3-1. (Continued)

and their efficiencies must be adjusted to account for pollutant removal by the existing device.

Operating Schedule (H, hours/year)

The annual hours of plant operation.

Fuel Usage. For each combustion source, the types, quantities, and sulfur and ash contents of all fuels presently used must be supplied.

Maximum Process Rate (R, BTU/hr). For industrial processes, the maximum process rate is used as the measure of plant capacity.

Emission Rates (E, ton/day). The actual amount of each pollutant emitted by each source.

Table 3-2.
Control Device Description

Wet Scrubbers or Wet Collectors (Device Codes: 001, 002, 003; used for particulates.

These are devices which use a liquid, commonly water, to remove particulates or gases directly from a gas stream. The removal is accomplished by contact, or through an increase in the collection efficiency of a second-stage collector by increasing the effective particle diameter. The simplest wet scrubber is a spray chamber into which water is injected by a spray nozzle. Wet scrubbers applied to a hot gas stream have the additional property of gas cooling and humidification.

Mechanical (Centrifugal) Collectors (007-009; used for particulates)

These are devices which remove particulate matter from a gas stream by using only the centrifugal force. Nothing is injected into the gas to combine with or entrain the particles. These devices use the centrifugal force created by spinning the exhaust gas stream to drive particulate matter from the gas. The spinning gas stream is set up inside a cylindrical container by tangential gas inlets, vanes, or fan action.

Electrostatic Precipitators (010, 011, 012; used for particulates)

These are devices which remove particles from a gas stream by electrically charging the suspended particles as the gas passes through a corona discharge. The charged particles are then collected on a grounded collection plate. High-voltage precipitators, which are the only electrostatic devices considered by the program, can be operated over a relatively wide range of collection efficiencies. These devices produce a low pressure drop and consequently have low operating costs for large gas volumes. Low-voltage precipitators are not considered since they are generally used for industrial hygiene purposes and not for air pollution control.

Gas Scrubber (013, used for sulfur oxides)

This is a device in which water (or another liquid) is brought into intimate contact with the effluent gas stream. The pollutants are removed by absorption or by chemical reaction. The cost elements of this device

Table 3-2. (Continued)

were expressly tailored to gas removal. While this device can be applied for particulate or mist removal, it is generally more costly than the alternate devices listed here. Consequently, the program applies this device for gas removal only.

Mist Elminators (014, 015; used for particulates)

These are devices designed to remove liquid droplets. The principal collection mechanisms are interception and impaction. Operation is much like that of fabric filters for dry particulates.

Fabric Filters (016, 017, 018; used for particulates)

These are devices which remove particles from a gas stream by passing the gas through fabric tubes or envelopes. A cake of collected particles, supported by the fabric, accomplishes the filtration. Very high efficiencies can be attained using fabric filters. A wide range of fabrics and cleaning techniques are available.

Afterburners (019, 020, 021, 022; used for particulates)

These are devices which remove pollutants by combustion. The direct-flame afterburner brings the gas stream into contact with a high-temperature flame to achieve rapid oxidation. The catalytic afterburner operates at a lower temperature by oxidizing the pollutants on the surface of a catalyst.

Flue Gas Desulfurization (039, 041, 042; used for sulfur oxides)

These control measures rely upon injection of various chemicals into the exit gas stream (alternatively, the reactive or catalytic material may be employed in a fixed of fluidized bed). The injected chemicals either react with sulfur oxide directly to produce a readily collectible solid or gas, or absorb the sulfur oxide by producing a physically bonded sulfate. The more promising methods for cleaning flue gases are:

Catalytic Oxidation (039)

This type of control for sulfur dioxide in the flue gas is a recently developed desulfurization process. After high-temperature oxidation of the SO_2 to SO_3, an absorbing tower procedure using

Table 3-2. (Continued)

sulfuric acid is employed. Sulfur is recovered as commercially saleable sulfuric acid. This process is reported to be applicable to larger existing installations and to new power generating stations, [Stites, et al., 1969].

Limestone Injection - Dry Process (041)

This control measure employs finely ground limestone which is injected into the boiler combustion zone. The limestone reacts with the sulfur oxides to form calcium sulfate. The sulfate is then removed from the gas stream by a precipitator or other particulate control device. The process is applicable to both new and existing coal fired electric generating facilities.

Limestone Injection - Wet Process (042)

This control measure employs the same basic injection of limestone as the dry process. However, instead of collecting calcium sulfate in the dry state, a liquid slurry of lime is used to remove the sulfate and any unreacted sulfur oxide. The process is applicable to basically the same sources as the dry process described above. The more expensive collection equipment needed may indicate that the wet process may be more often applied to new installations.

By-Product Manufacturing (043, 044, 045; used for sulfur oxides)

This capitalizes on the fact that either elemental sulfur or sulfuric acid may be manufactured from a sulfur oxide-rich gas. Both products are in relatively high demand in industrial markets, and often can bring a price high enough to substantially offset the cost of controlling emissions. Cases in which sulfuric acid and sulfur plants are used as control measures are not to be confused with cases where similar plants are operated independently in such a manner as to be emission sources themselves. Clearly, a sulfur plant will not be considered a control measure for a sulfur plant emission source.

Table 3-3. Preset Device Data

DEVICE		RATED EFF		MANUFACTURERS PRICE COEFF			INST	CHEM	DISP COST		LABOR QUANTITY*				DEV	PRS	FUEL
ID	NAME	SO_2	PART	1	2	3	FACT	COST	SO_2	PART	SML	MED	LGE	X-LGE	LEE	DRP	FACT
1	WET SCRUBBER HI EFFIC	0.0	98.0	0.289E 01	0.228E 00	0.0	2.00	0.0	0.0	1.0	0.50	1.00	2.00	4.00	15	20.0	0.0
2	WET SCRUBBER MED EFFIC	0.0	90.0	0.289E 01	0.228E 00	0.0	2.00	0.0	0.0	1.0	0.38	0.75	1.50	3.00	15	4.0	0.0
3	WET SCRUBBER LO EFFIC	0.0	80.0	0.126E 01	0.145E 00	0.0	2.00	0.0	0.0	1.0	0.38	0.75	1.50	3.00	15	3.0	0.0
7	CYCLONE HI EFFIC	0.0	85.0	0.241E 01	0.197E 00	0.0	1.00	0.0	0.0	1.0	0.25	0.50	1.00	2.00	15	4.0	0.0
8	CYCLONE MED EFFIC	0.0	75.0	0.151E 01	0.157E 00	0.0	1.00	0.0	0.0	1.0	0.25	0.50	1.00	2.00	15	3.0	0.0
9	CYCLONE LO EFFIC	0.0	60.0	0.244E 00	0.990E-01	0.0	1.00	0.0	0.0	1.0	0.25	0.50	1.00	2.00	15	2.0	0.0
10	ELECT PRECIP HI EFFIC	0.0	99.0	0.424E 02	0.623E 00	0.0	1.00	0.0	0.0	1.0	0.50	1.50	3.00	6.00	15	.5	0.0
11	ELECT PRECIP MED EFFIC	0.0	95.0	0.312E 02	0.441E 00	0.0	1.00	0.0	0.0	1.0	0.50	1.50	3.00	6.00	15	.5	0.0
12	ELECT PRECIP LO EFFIC	0.0	90.0	0.197E 02	0.318E 00	0.0	1.00	0.0	0.0	1.0	0.50	1.50	3.00	6.00	15	.5	0.0
13	GAS SCRUBBER	80.0	80.0	0.317E 01	0.251E 00	0.0	2.00	10.0	0.0	1.0	0.38	0.75	1.50	3.00	15	5.0	0.0
14	MIST ELIMINATOR HI VEL	0.0	99.0	0.266E 01	0.325E 00	0.0	1.00	0.0	0.0	0.0	0.25	0.50	1.00	2.00	15	10.0	0.0
15	MIST ELIMINATOR LO VEL	0.0	85.0	0.177E 01	0.217E 00	0.0	1.00	0.0	0.0	0.0	0.25	0.50	1.00	2.00	15	5.0	0.0
16	FABRIC FILTER HI TEMP	0.0	99.0	0.145E 01	0.838E 00	0.0	1.00	0.0	0.0	1.0	0.50	1.25	2.50	5.00	15	5.0	0.0
17	FABRIC FILTER MED TEMP	0.0	99.0	0.348E 01	0.448E 00	0.0	1.00	0.0	0.0	1.0	0.50	1.25	2.50	5.00	15	5.0	0.0
18	FABRIC FILTER LO TEMP	0.0	99.0	0.266E 01	0.325E 00	0.0	1.00	0.0	0.0	1.0	0.50	1.25	2.50	5.00	15	5.0	0.0
19	CATALYTIC AFTERBURNER	0.0	95.0	0.755E 01	0.151E 01	0.0	1.00	0.0	0.0	0.0	0.25	0.50	1.00	2.00	15	1.0	0.49
20	CATALYTIC AB WITH HE	0.0	95.0	0.755E 01	0.151E 01	0.0	2.00	0.0	0.0	0.0	0.25	0.50	1.00	2.00	15	1.0	0.24
21	DIRECT FLAME AFTERBURNER	0.0	95.0	0.571E 01	0.117E 01	0.0	1.00	0.0	0.0	0.0	0.13	0.25	0.50	1.00	15	1.0	1.00
22	DIRECT FLAME AB WITH HE	0.0	95.0	0.571E 01	0.117E 01	0.0	2.00	0.0	0.0	0.0	0.13	0.25	0.50	1.00	15	1.0	0.40
39	CATALYTIC OXYDATION	90.0	0.0	-0.124E 02	0.167E 01	0.0	0.0	0.0	-27.6	0.0	0.0	0.0	0.0	0.0	15	41.5	0.0
41	DRY LIMESTONE INJECTION	50.0	0.0	0.0	0.995E-06	-0.603E-16	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	15	0.0	0.0
42	WET LIMESTONE INJECTION	80.0	98.0	0.111E-05	0.481E-16	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	15	0.0	0.0
43	H2504 PLANT-CONTACT	97.5	0.0	0.0	0.800E 00	0.0	0.0	0.0	-27.6	0.0	0.0	0.0	0.0	0.0	20	0.0	0.0
44	H2504 PLANT-2 CONTACT	99.5	0.0	0.0	0.800E 00	0.0	0.0	0.0	-27.6	0.0	0.0	0.0	0.0	0.0	20	0.0	0.0
45	SULFUR PLANT	95.0	0.0	0.0	0.810E 00	0.0	0.0	0.0	-15.0	0.0	0.0	0.0	0.0	0.0	20	0.0	0.0

*Small plant; ACFM ≤ 40E3, medium plant; 40E3 < ACFM ≤ 250E3, large plant; 250E3 < ACFM ≤ 1.E6, extra large plant; ACFM ≥ 1.E6.

The cost equations were then used to determine the changes in annual control cost for each device as a function of the regional cost input parameters: interest rate, electricity cost, water cost, natural gas cost, and labor cost for four plant size ranges. These results are presented in Table 3-5 for small (ACFM≤40E3), medium (40E3≤ACFM≤250E3), large (250E3≤ACFM≤1·E6), and extra large (ACFM≤1·E6). A limited number of parameter value assumptions were required for the construction of this table and are listed below.

Sensitivity Parameter	Assumptions
Interest rate	None
Electricity cost Water cost	• devices 001, 002, 003 and 0013: T = 500, 425, 375, and 300 degrees Kelvin for small, medium, large, and extra large plants, respectively. • Operating time = 8760 hours.
Natural gas cost Labor cost	• Operating time = 8760 hours
General	Preset data (Table 3-3)

This table is used to construct the Annual Control Cost variation for a given variation in the input cost parameters. For example, if the regional labor cost was known to the nearest \$.2 and the electricity cost to the nearest \$.005, the maximum annual control cost variation for the wet scrubbers would be \$1,750 plus \$8,289 or about \$10,000. To obtain a general relationsihp between the variation of control cost with variations in the cost parameters, specific cost data must be assumed. Then, percent control cost deviation as a function of percent cost parameter deviation can be determined. Table 3-6 presents typical control cost data for four plant size ranges defined for Table 3-5. This data was obtained from surveying data from several regions. Table 3-6 also shows the resulting annual control cost for each device plant size

A

Figure 3-5. Cont

	ANNUAL CAPITAL CHARGE				OPERATING AND MAINT							
	Total Installed Cost				Electricity			Liquid			Chemical	
Dev ID	Purchase Cost	1+N	C.R.F.		Quantity	Cost		Quantity	Cost		Quantity	Cos
001	(2886.+.288 ACFM)	3	(.00702 C_1+.06088)	+	1.955 10^{-4} 20 $\overline{ACFM}$ H	C_e	+	3. 10^{-2} $\overline{ACFM}$ H	C_w	+	N/A	
002	(2886.+.288 ACFM)	3	(.00702 C_1+.06088)	+	1.955 10^{-4} 4 $\overline{ACFM}$ H	C_e	+	3. 10^{-2} $\overline{ACFM}$ H	C_w	+		
003	(1257.+.145 ACFM)	3	(.00702 C_1+.06088)	+	1.955 10^{-4} 3 $\overline{ACFM}$ H	C_e	+	3. 10^{-2} $\overline{ACFM}$ H	C_w	+		
007	(2413.+.197 ACFM)	2	(.00702 C_1+.06088)	+	1.955 10^{-4} 4 ACFM H	C_e	+	N/A		+		
008	(1507.+.157 ACFM)	2	(.00702 C_1+.06088)	+	1.955 10^{-4} 3 ACFM H	C_e	+			+		
009	(244.+.099 ACFM)	2	(.00702 C_1+.06086)	+	1.955 10^{-4} 2 ACFM H	C_e	+			+		
010	(42413.+.623 ACFM)	2	(.00702 C_1+.06088)	+	(1.055 10^{-4} .5 ACFM H +.34 10^{-3} ACFM H)	C_e	+			+		
011	(31243.+.441 ACFM)	2	(.00702 C_1+.06088)	+	(1.955 10^{-4} .5 ACFM H +.26 10^{-3} ACFM H)	C_e	+			+		
012	(19695.+.318 ACFM)	2	(.00702 C_1+.06088)	+	(1.955 10^{-4} .5 ACFM H +.19 10^{-3} ACFM H)	C_e	+	N/A		+	N/A	
013	(3175.+.25 ACFM)	3	(.00702 C_1+.06088)	+	1.955 10^{-5} 5 $\overline{ACFM}$ H	C_e	+	3 10^{-2} $\overline{ACFM}$ H	C_w	+	$E_s \eta_s$H/(8 Shift)	1
014	(2658.+.325 ACFM)	2	(.00702 C_1+.06088)	+	1.955 10^{-4} 10 ACFM H	C_e	+	N/A		+	N/A	
015	(1772.+.217 ACFM)	2	(.00702 C_1+.06088)	+	1.955 10^{-4} 5 ACFM H	C_e	+			+		
016	(1448.+.838 ACFM)	2	(.00702 C_1+.06088)	+	1.955 10^{-4} 5 ACFM H	C_e	+			+		
017	(3478.+.448 ACFM)	2	(.00702 C_1+.06088)	+	1.955 10^{-4} 5 ACFM H	C_e	+			+		
018	(2658.+.325 ACFM)	2	(.00702 C_1+.06088)	+	1.955 10^{-4} 5 ACFM H	C_e	+			+		
019	(7550.+1.515 $\overline{\overline{ACFM}}$)^1	2	(.00702 C_1+.06088)	+	1.955 10^{-4} 1 $\overline{\overline{ACFM}}^1$H	C_e	+			+		
020	(7550.+1.515 $\overline{\overline{ACFM}}$)^2	3	(.00702 C_1+.06088)	+	1.955 10^{-4} 1 $\overline{\overline{ACFM}}^2$H	C_e	+			+		
021	(5713.+1.174 $\overline{\overline{ACFM}}$)^3	2	(.00702 C_1+.06088)	+	1.955 10^{-4} 1 $\overline{\overline{ACFM}}^3$H	C_e	+			+		
022	(5713.+1.174 $\overline{\overline{ACFM}}$)^4	3	(.00702 C_1+.06088)	+	1.955 10^{-4} 1 $\overline{\overline{ACFM}}^4$H	C_e	+			+		
039	ALog$_{10}$(-12.41 + 1.671log$_{10}$ R+3)	1	(.00702 C_1+.06088)	+	1.955 10^{-4} 41.5 ACFM H	C_e	+			+		
041	(9.95 10^{-7} R-6.03 10^{-17} R^2)	1	(.00702 C_1+.06088)	+	N/A		+			+		
042	(1.108 10^{-6} R-4.81 10^{-17} R^2+9.572 10^{-8} S R-4.16 10^{-13} S R^2)	1	(.00702 C_1+.06088)	+			+			+		
043	ALog$_{10}$[a+.8log$_{10}$(E_s/2) + 6]	1	(.00746 C_1+.0424)	+			+			+		
044	ALog$_{10}$[a+.8log$_{10}$(E_s/2) + 6]	1	(.00746 C_1+.0424)	+			+			+		
045	ALog$_{10}$[a+.8log$_{10}$(E_s/2) + 6]	1	(.00746 C_1+.0424)	+	N/A		+	N/A		+	N/A	

NOTES:

For devices 010,011,012,016,017,018; if T_o > 532°K, new ACFM value must be calculated and cooling cost must be added to O&M cost.

N = installation factor (pre-set)

H = operating time - hr/yr

L = labor quantity (pre-set)

C_1,C_e,C_w,C_e = cost of interest(%), electricity($/kwhr), water($/gal), and labor ($/hr)

ALog$_{10}$ = anti logarithm to the base 10.

NOTES: (continued)

$\overline{ACFM}$ = ACFM (.097 + 266.4/T_o)

$\overline{\overline{ACFM}}^1$ = ACFM (1 + 288/T_o)

$\overline{\overline{ACFM}}^2$ = ACFM (1 + 139/T_o)

$\overline{\overline{ACFM}}^3$ = ACFM (1 + 556/T_o)

$\overline{\overline{ACFM}}^4$ = ACFM (1 + 222/T_o)

NOTES: (continued

η'_p, η'_s = applied efficienc

E_p, E_s = emission rates, t

R = rated capacity, E

a,b = calculated cost c

P_c = coal burned, ton/

S = coal sulfur conte

B

rol Costs Equations.

ENANCE COST											
		Fuel			Disposal			Labor			Other
t		Quantity	Cost		Quantity	Cost		Quantity	Cost		
	+	N/A		+	$E_p\ \eta'_p$ H/(8 Shift)	1	+	H L	C_e	+	N/A
	+			+	$E_p\ \eta'_p$ H/(8 Shift)	1	+	H L	C_e	+	
	+			+	$E_p\ \eta'_p$ H/(S Shift)	1	+	H L	C_e	+	
	+			+	$E_p\ \eta'_p$ H/(8 Shift)	1	+	H L	C_e	+	
	+			+	$E_p\ \eta'_p$ H/(8 Shift)	1	+	H L	C_e	+	
	+			+	$E_p\ \eta'_p$ H/(8 Shift)	1	+	H L	C_e	+	
	+			+	$E_p\ \eta'_p$ H/(8 Shift)	1	+	H L	C_e	+	
	+			+	$E_p\ \eta'_p$ H/(8 Shift)	1	+	H L	C_e	+	
	+			+	$E_p\ \eta'_p$ H/(8 Shift)	1	+	H L	C_e	+	
0	+			+	$E_p\ \eta'_p$ H/(8 Shift)	1	+	H L	C_e	+	
	+			+	N/A		+	H L	C_e	+	
	+			+	N/A		+	H L	C_e	+	
	+			+	$E_p\ \eta'_p$ H/(8 Shift)	1	+	H L	C_e	+	
	+			+	$E_p\ \eta'_p$ H/(8 Shift)	1	+	H L	C_e	+	
	+	N/A		+	$E_p\ \eta'_p$ H/(8 Shift)	1	+	H L	C_e	+	
	+	$.49\ \overline{ACFM}^1\ H$	C_g	+	N/A		+	H L	C_e	+	
	+	$.245\ \overline{ACFM}^2\ H$	C_g	+			+	H L	C_e	+	
	+	$1.\ \overline{ACFM}^3\ H$	C_g	+			+	H L	C_e	+	
	+	$.404\ \overline{ACFM}^4\ H$	C_g	+	N/A		+	N/A		+	N/A
	+	N/A		-	$E_s\ \eta'_s$ H/(8 Shift)	27.6	+			+	$[\mathrm{ALog}_{10}(-12.41+1.67\mathrm{log}_{10}{}^{R+3}]\ .05$
	+			+	N/A		+			+	$365\ P_c(.17+.07\ S\ 2)+25\ 10^3$
	+			+	N/A		+			+	$365\ P_c(.196+.0382\ S\ 2)+130\ 10^3$
	+			-	$E_s\ \eta'_s$ H/(8 Shift)	27.6	+			-	$\mathrm{ALog}_{10}[a+.8\ \mathrm{Log}_{10}(E_s/2)+6]/20$ $+\mathrm{ALog}_{10}[b+.75\mathrm{Log}_{10}E_s+3]$
	+			-	$E_s\ \eta'_s$ H/(8 Shift)	27.6	+			-	$\mathrm{ALog}_{10}[a+.8\ \mathrm{Log}_{10}(E_s/2)+6]/20$ $+\mathrm{ALog}_{10}[b+.75\mathrm{Log}_{10}E_s+3]$
	+	N/A		-	$E_s\ \eta'_s$ H/(8 Shift)	15.	+	N/A		-	$\mathrm{ALog}_{10}[a+.81\mathrm{Log}_{10}(E_s/2)+6]/20$ $+\mathrm{ALog}_{10}[b+.75\mathrm{Log}_{10}E_s+6]$

ies, %
on/day
TU/hr
oefficients
day
nt, %

Table 3-5. Regional Cost Sensitivity - Small Plant ($20 \cdot 10^3$ ACFM)

Device ID	Change in Annual Control Cost - \$ 10^3				
	Per % Interest	Per .01 \$/kwhr Elec. Cost	Per .001 \$/gal Water Cost	Per .0001 \$/ft^3 Gas Cost	Per \$/hr Labor Cost
001	.161	4.310	.311	N/A	4.370
002	.161	.863	.311		3.325
003	.088	.647	.311		3.325
007	.089	1.370	N/A		2.187
008	.065	1.027			2.187
009	.045	.685			2.187
010	.770	.766			4.376
011	.563	.626			4.376
012	.366	.503	N/A		4.376
013	.173	1.078	.311		3.325
014	.129	3.424	N/A		2.187
015	.086	1.712			2.187
016	.256	1.712			4.376
017	.175	1.712			4.376
018	.129	1.712		N/A	4.376
019	.777	.540		8.585	2.187
020	.975	.438		4.291	2.187
021	.777	.723		17.522	2.187
022	.834	.494		7.079	2.187
039	.022	14.042		N/A	N/A
041	.348	N/A			
042	.479				
043	N/A				
044					
045	N/A	N/A	N/A	N/A	N/A

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Table 3-5. (continued) - Medium Plant (150 10^3 ACFM)

Device ID	Change in Annual Control Cost - $ 10^3 Per % Interest	Per .01 $/kwhr Elec. Cost	Per .001 $/gal Water Cost	Per .0001 $/ft^3 Gas Cost	Per $/hr Labor Cost
001	.970	37.177	2.854	N/A	8.750
002	.970	7.435	2.854	│	6.563
003	.485	5.577	2.854	│	6.563
007	.449	10.271	N/A	│	4.376
008	.352	7.704	│	│	4.376
009	.212	5.136	│	│	4.376
010	1.908	5.747	│	│	13.126
011	1.368	4.696	│	│	13.126
012	.947	3.777	N/A	│	13.126
013	.860	9.295	2.854	│	8.751
014	.722	25.677	N/A	│	4.376
015	.482	12.840	│	│	4.376
016	1.760	12.840	│	│	10.939
017	.993	12.840	│	│	10.939
018	.722	12.840	│	N/A	10.939
019	5.459	4.087	│	64.388	4.375
020	6.513	3.234	│	32.180	4.375
021	5.788	5.623	│	131.412	2.188
022	5.767	3.709	│	53.092	2.188
039	.728	105.231	│	N/A	N/A
041	2.727	N/A	│	│	│
042	3.850	│	│	│	│
043	N/A	│	│	│	│
044	│	│	│	│	│
045	N/A	N/A	N/A	N/A	N/A

Table 3-5. (continued) - Large Plant (600·10^3 ACFM)

Device ID	Per % Interest	Per .01 \$/kwhr Elec. Cost	Per .001 \$/gal Water Cost	Per .0001 \$/ft^3 Gas Cost	Per \$/hr Labor Cost
	Change in Annual Control Cost - \$ 10^3				
001	3.700	165.774	12.73	N/A	17.502
002	3.700	33.154	12.73		13.127
003	1.859	24.868	12.73		13.127
007	1.694	41.100	N/A		8.751
008	1.344	30.828			8.751
009	.838	20.550			8.751
010	5.845	23.006			26.254
011	4.155	18.806			26.254
012	2.956	15.121	N/A		26.254
013	3.239	41.445	12.73		13.127
014	2.776	102.756	N/A		8.751
015	1.853	51.378			8.751
016	7.082	51.378			21.878
017	3.824	51.378			21.878
018	2.776	51.378		N/A	21.878
019	22.681	18.153		257.551	8.751
020	26.393	14.078		128.730	8.751
021	24.647	24.130		525.647	4.376
022	23.739	16.355		212.368	4.376
039	6.680	421.251		N/A	N/A
041	9.538	N/A			
042	13.736				
043	14,690				
044	17,690				
045	26,810	N/A	N/A	N/A	N/A

Table 3-5. (continued) - Extra Large Plant ($2000 \cdot 10^3$ ACFM)

Device ID	Change in Annual Control Cost - $\$ 10^3$				
	Per % Interest	Per .01 $/kwhr Elec. Cost	Per .001 $/gal Water Cost	Per .0001 $/ft^3 Gas Cost	Per $/hr Labor Cost
001	12.195	674.743	51.772	N/A	35.000
002	12.195	134.947	51.772		26.254
003	6.136	101.219	51.772		26.254
007	5.566	137.000	N/A		17.502
008	4.431	102.760			17.502
009	2.784	68.500			17.502
010	18.095	76.686			52.507
011	12.825	62.686			52.507
012	9.209	50.406	N/A		52.507
013	10.642	168.691	51.772		26.254
014	9.166	342.520	N/A		17.502
015	6.120	171.260			17.502
016	23.558	171.260			43.756
017	12.632	171.260			43.756
018	9.166	171.260		N/A	43.756
019	83.511	67.133		858.502	17.502
020	93.543	50.110		429.099	17.502
021	94.159	97.720		1752.156	8.751
022	86.186	59.597		707.892	8.751
039	68.299	1257.586		N/A	N/A
041	26.678	N/A			
042	43.460				
043	25,610				
044	30,760				
045	47,100	N/A	N/A	N/A	N/A

Table 3-6. Example Control Cost Values

Parameter	Small Plant	Medium Plant	Large Plant	Extra Large Plant
ACFM(1)	$20 \cdot 10^3$	$150 \cdot 10^3$	$600 \cdot 10^3$	$2000 \cdot 10^3$
H-hrs/yr(2)	8760	8760	8760	8760
T-°k	500	425	375	300
C_i-%	8.5	8.5	8.5	8.5
C_e-$/kwhr	.018	.017	.016	.016
C_w-$/gal	.002	.002	.002	.002
C_g-$/cu.ft.	$.44 \cdot 10^{-3}$	$.44 \cdot 10^{-3}$	$.44 \cdot 10^{-3}$	$.44 \cdot 10^{-3}$
C_ℓ-$/hr	3.	3.	3.	3.
R-BTU/hr	$50 \cdot 10^6$	$400 \cdot 10^6$	$1500 \cdot 10^6$	$6000 \cdot 10^6$
E_p-ton/day	1.	10.	100.	300.
N_p-%(2)	0.	0.	0.	0.
E_s-ton/day	1.	5.	50.	100.
M_s-%(2)	0.	0.	0.	0.
P_c-ton/day	60.	300.	3000.	6000.
S-%	3.	3.	3.	3.
		Annual Device Cost		
Device ID				
001	24,693	115,452	442,556	1,604,917
002	15,295	58,008	314,313	706,202
003	13,608	46,143	165,787	537,266
007	9,966	41,417	152,150	460,425
008	9,129	35,021	126,060	375,185
009	8,343	27,703	95,440	275,656
010	27,710	85,558	252,138	699,433
011	23,971	74,358	214,937	582,190
012	20,436	65,377	186,634	495,967
013	18,766	80,079	362,005	1,014,586
014	12,662	69,203	238,344	757,948
015	9,986	43,251	140,303	431,641
016	19,833	88,955	305,619	918,269
017	18,442	75,340	249,649	730,700

(contd.)

(1) Defines plant size.

(2) No typical values apply, therefore conservative value used.

Table 3-6. (continued)

Annual Device Cost

Device ID	Small Plant	Medium Plant	Large Plant	Extra Large Plant
018	17,651	70,694	231,700	671,192
019	59,003	400,551	1,612,460	5,474,634
020	43,318	275,511	1,102,932	3,730,472
021	98,639	697,113	2,822,121	9,611,703
022	53,274	348,919	1,415,832	4,819,625
039	16,751	151,315	382,906	2,764,309
041	43,900	136,421	834,787	1,775,094
042	147,446	242,198	826,819	1,803,098
043	N/A	N/A	568,667	815,534
044	|	|	588,517	849,934
045	N/A	N/A	1,396,614	2,393,477

combination. Devices 042, 043, and 045 (by-product manufacturing) are not applied to the small and medium plant sizes because they failed to meet the minimum efficiency requirements. Table 3-7 shows the average (over plant size) percent contribution to total cost for each of the control cost equation components. It is obvious from this table that the fuel, labor, and electricity costs are the dominant parameters.

Now, using the data from Table 3-6, the percent deviation in annual control cost due to a specified deviation in each cost parameter can be calculated for each device plant size combination. Table 3-8 presents the maximum annual control cost deviation (from the four plant sizes) for each device resulting from a ten percent cost parameter deviation. These results show that a ten percent deviation for all cost parameters results in less than a nineteen percent error in total annual control cost (obtained by summing the individual deviations of the worst case, device 039). Since the device costs utilize the cost parameters in different ways, the ten percent restriction may be too severe for some of the cost parameters. Assuming a total control cost deviation of twenty percent as an upper limit, the maximum uncertainty of each cost parameter can be determined from Table 3-8. These values are shown in Table 3-9.

Table 3-7. Typical Control Cost Breakdown (% of Total)

DEVICE ID	ANNUAL CAPITAL CHARGE	OPERATIONS AND MAINTENANCE COST						
		ELECT	LIQ	CHEM	FUEL	DISP	LABOR	OTHER
001	14	57	5	N/A	N/A	6	18	N/A
002	29	53	11			11	26	
003	19	22	13			12	34	
007	19	42	N/A			14	25	
008	18	38				15	29	
009	14	33				16	37	
010	39	13				9	39	
011	32	12				11	45	
012	26	11	N/A	N/A		12	51	
013	17	19	7	29		6	22	
014	19	66	N/A	N/A		N/A	15	
015	21	54				N/A	25	
016	37	26				8	29	
017	24	31				10	35	
018	19	33			N/A	10	38	
019	24	2			71	1	2	
020	41	2			51	2	4	
021	15	1			82	1	1	
022	28	2			67	2	1	N/A
039	36	N/A			N/A	N/A	N/A	64*
041	19					N/A		81
042	24					N/A		76
043	37					Credit		63*
044	45					Credit		55*
045	26	N/A	N/A	N/A	N/A	Credit	N/A	174*

*Includes disposal credit.

Table 3-8. Percent Annual Control Cost Deviation Due To 10% Cost Parameter Deviation

Device ID	% Annual Cost Deviation (By Cost Parameter)						
	Interest	Electricity	Water	Chemical	Natural Gas	Disposal	Labor
001	1/2	7	1	N/A	N/A	1	5
002	1	3	1			2	7
003	1	3	2			2	7
007	1	5	N/A			2	7
008	1	4				2	8
009	1/2	4				2	5
010	1	2				2	5
011	1	2				2	6
012	1	2	N/A	N/A		2	5
013	1/2	3	1	3		1	5
014	1	7	N/A	N/A		N/A	7
015	1	6				N/A	7
016	1	3				1	7
017	1	4				1	7
018	1	4			N/A	2	1
019	1	2			7	2	2
020	1	2			5	3	1
021	1/2	2			8	1	1
022	1	2			6	2	N/A
039	1	7			N/A	11	
041	1	N/A				N/A	
042	1	N/A	N/A	N/A	N/A	N/A	N/A

Table 3-9.

Suggested Maximum Control Cost Parameter Uncertainty

Parameter	Maximum Parameter Uncertainty (%)
Interest Rate	20
Electricity Cost	10
Water Cost	20
Chemical Cost	20
Natural Gas Cost	10
Disposal Cost	10
Labor Cost	10

4.0 PARAMETER SENSITIVITY SUMMARY

The analysis of Chapters 2.0 and 3.0 presented techniques for determining the sensitivity of the effective stack height parameters (with respect to maximum pollutant concentration, χ_m) and control cost parameters (with respect to annual control device cost). As a general guide, the set of maximum parameter sensitivities which would result in less than 20% error in χ_m or total annual control device cost were obtained (Table 4-1). A more common situation arises when only a few parameters are not known with sufficient accuracy. To determine the impact in such cases, an analysis using the specific parameter values in question must be performed.

Effective Stack Parameters

The sensitivity of each of the effective stack height parameters: h, V, D, T, P and T_a is highly dependent on the nominal values assumed for the complete set. For this reason, the sensitivity of a given parameter should be determined by using the best estimate for each remaining parameter. The procedure is to first calculate H_o from Equation (1) using the nominal parameter values.

$$H = \frac{VD}{4.5} \left[1.5 + 2.68E - 3PD \left(1 - T_a/T\right)\right] \tag{1}$$

Then, H is calculated using the limit value of the parameter in question. Finally, the corresponding maximum concentration sensitivity is determined from Equation (2) (or from Figure 2-4, Chapter 2.0).

$$\frac{\chi_m}{\chi_{m_o}} = \left(\frac{H}{H_o}\right)^{-2.502} \tag{2}$$

To maintain less than a maximum possible error of 20%, the ratio H/H_o should be $1.05 \geq H/H_o \geq .95$.

Control Cost Parameters

To determine the cost sensitivity for a particular source device combination, the basic control cost equations presented in Table 3-4 should be used. If the general impact of a large cost parameter uncertainty is desired, Table 3-8 should be reconstructed using the appropriate parameter uncertainty values.

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Table 4-1. Suggested Maximum Parameter Range

Parameter	Parameter Range (%)
Stack height (meters)	±3
Exit velocity (meters/second)	±5
Exit diameter (meters)	±3
Exit temperature (degrees Kelvin)	±3
Ambient pressure (millibars)	±5
Ambient temperature (degrees Kelvin)	±5
Interest rate (percent)	20
Electricity cost (\$/kwhr)	10
Water cost (\$/gallon)	20
Chemical cost (\$/ton)	20
Natural gas cost (\$/ft^3)	10
Disposal cost (\$/ton)	10

5.0 REFERENCES

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APPENDIX A

DIFFUSION MODEL DESCRIPTION

The atmospheric diffusion model is based upon a diffusion model developed by Martin and Tikvart [1968]. The basic output of the model is in the form of calculated long term average pollutant concentrations at ground level.

The Martin-Tikvart model calculates concentrations downwind from a set of point and area sources on the basis of the Pasquill [1962] point source formulation. A description of the process follows:

The stack in Figure A-1 represents a typical elevated point source. The coordinate system for this source has its origin at ground level at the base of the stack (i.e., directly below the effective point of emission). The x-axis extends horizontally in the mean wind direction. The y-axis is horizontal in the cross-wind (and cross-plume) direction. The z-axis is vertical.

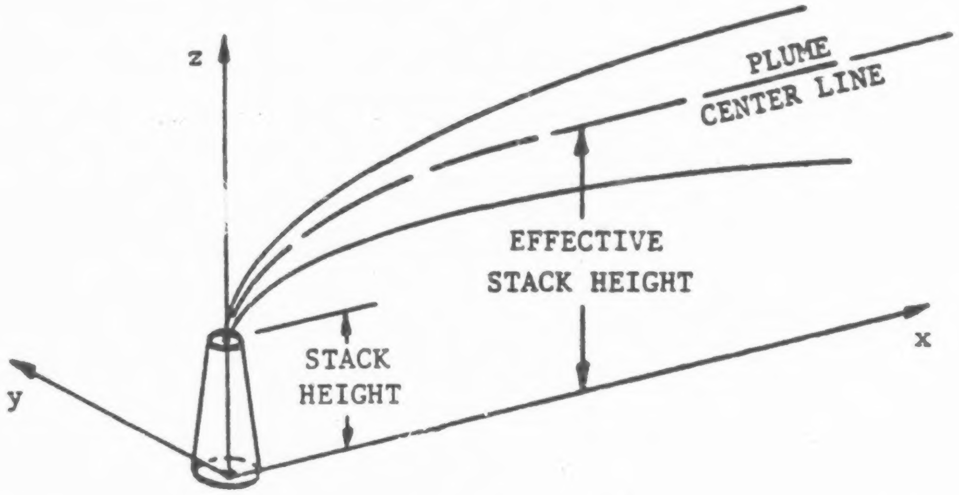

Figure A-1. Source Coordinate System for Diffusion Model.

Although the change in wind direction is a continuous function over the long-term period, for computation purposes discrete wind directions are specified with respect to a 16-point compass, corresponding to 22.5-degree sectors. For seasonal or longer periods it is often assumed that all wind directions within a given 22.5-degree sector occur with equal frequency. Thus, the effluent could be assumed to be uniformly distributed in the horizontal within the sector. However, this assumption would result in discontinuities in calculated concentrations at sector boundaries. A more reasonable distribution is obtained by using a linear interpolation between sector centerlines. Thus, the concentration at a given receptor location is composed of proportional contributions from both the sector containing the receptor and from the nearest adjacent sector. The linear interpolation term is given by (c-y)/c, where y is the crosswind distance between the receptor and the sector centerline, and c is the sector width at the receptor location. This concept is illustrated in Figure A-2. Note that a SSW wind affects the receptor to the NNE of the source.

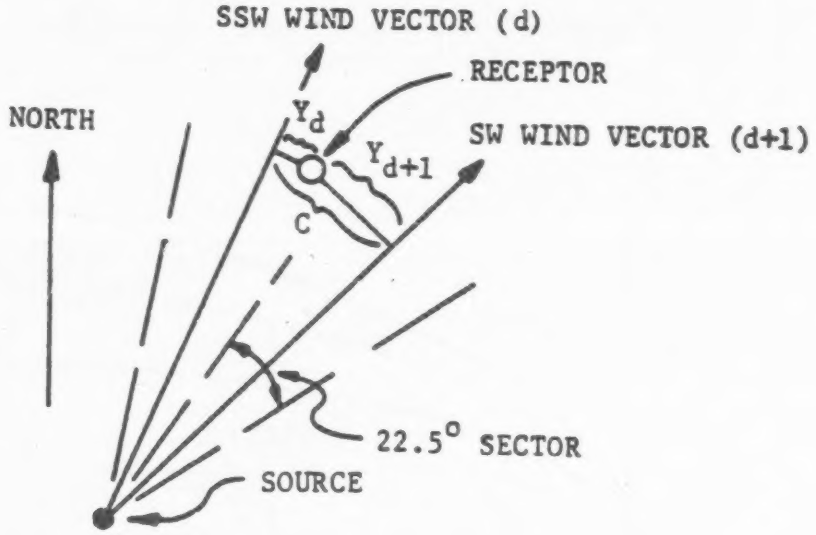

Figure A-2. Interpolation of Wind Directions.

The "effective stack height" (or effective height of emission release) is the height at which the plume center line becomes horizontal. The effective stack height is the sum of the physical stack height and an incremental factor related to the buyancy and vertical momentum of the effluent.

The concentration, χ, at a position (x,y,z) for pollutants emitted at (0,0,h) is given by

$$\chi(x,y,z;\ h) = \frac{10^6 Q}{2\pi\sigma_y\sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{z-h}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+h}{\sigma_z}\right)^2\right]\right\} \qquad (1)$$

where:

$\chi(x,y,z;\ h)$ = pollutant concentration, micrograms/meter^3, at point x,y,z for an effective stack height h.

Q = emission rate, grams/sec.

u = mean wind speed, meters/sec.

σ_y, σ_z = standard deviation of the plume concentration distribution in the cross-plume and vertical directions, meters. (σ_y and σ_z are given as functions of downwind distance and atmospheric stability, Gifford [1961]).

Ground-level concentration estimates are obtained by setting $z = 0$ in Equation (1), resulting in

$$\chi\ (x,y,z;\ h) = \frac{10^6 Q}{\sigma_y \pi \sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{h}{\sigma_z}\right)^2\right] \qquad (2)$$

For a source which emits at a constant rate from hour to hour and day to day, Equation (2) can be modified to yield estimates of long-term (annual or seasonal) average concentrations if applicable stability wind rose data are available. A wind rose tabulates the frequency of occurrence for each wind direction and wind speed class for the time period under consideration. A stability wind rose contains the same information, but it is further divided according to atmospheric stability classes.

Use of the linear crosswind distribution requires that the form of Equation (2) be changed to reflect a univariate Gaussian distribution:

$$\chi = \frac{2Q\cdot 10^6 (c-y) \; / \; c}{\sigma_z u \sqrt{2\pi} \; (2\pi x/16)} \exp \left[-\frac{1}{2} \left(\frac{h}{\sigma_z} \right)^2 \right] \qquad (3)$$

When an elevated stable layer occurs locally, the estimated pollutant concentrations are calculated with the assumption that all the effluent remains within the mixing layer height L, where L is defined as the vertical distance from the ground to the base of the stable layer. For the model calculations, σ_z is considered to increase in the downwind direction until it reaches a distance x_L at which $\sigma_z = 0.47L$. Up to this distance, the Gaussian vertical distribution is assumed, and Equation (3) is appropriate. At distance x_L the trapping effect of the elevated stable layer begins to be effective, and uniform mixing below the base of the stable layer is assumed to occur at downwind distance $2x_L$. For distances $x \geq 2x_L$, the average concentration is calculated with the assumption that the plume is uniformly mixed in the vertical:

$$\chi = \frac{10^6 Q(c-y)/c}{Lu(2\pi x/16)} \qquad (4)$$

For distances between x_L and $2x_L$, χ is determined by a linear interpolation between Equation (3), evaluated at x_L, and Equation (4), evaluated at $2x_L$.

For a specific receptor (r) and source (s) configuration, an estimate of χ_{rs} for each pollutant is obtained by choosing a representative wind speed for each wind speed class and solving the appropriate equation for every wind speed and stability class appropriate for the time period in the geographical area of interest. The average concentration, χ_{rs}, is obtained by summing all concentrations and weighting each one according to its frequency for the particular wind direction, wind speed class, and stability class. The expression for average concentration for a given pollutant is:

$$\chi_{rs} = \sum_{d=1}^{16} \sum_{n=1}^{6} \sum_{m=1}^{5} F_{dnm} \; \chi_{dnm} \qquad (5)$$

where:

F_{dnm} = normalized frequency during the period of interest for wind direction interval d, wind speed class n, and stability class m

χ_{dnm} = average ground-level concentration calculated from Equation (3) or (4) as appropriate.

For each of the 16 wind direction intervals, wind speed is defined in six categories and stability class in five categories. Thus a three-dimensional array of 480 categories is established. However, only a few of these wind directions result in non-zero contributions for specific source-receptor pairs. Thus the computation time is reduced significantly. Vertical variations in wind speed and wind direction are not accounted for in the present model.

The representative speeds associated with the six climatological wind speed categories (0-3, 4-6, 7-10, 11-16, 17-21 and >21 knots), are given by the five mid-interval values of 0.67, 2.46, 4.47, 6.93 and 9.61 meters per second, and by 12.52 meters per second (25.5 knots) for the >21 knots category.

The five stability categories (S = 1, 2, 3, 4 and 5, in order of increasing atmospheric stability) are defined on the basis of the criteria stated by Turner [1964]. Stability in the lowest part of the atmosphere is determined primarily by the net radiation and local wind speed.

Turner's classification is based upon ground-level meteorological observations only (surface wind speed, cloud cover, ceiling), supplemented by solar elevation data (latitude, time of day, and time of year); thus the stability estimates can be obtained for any Weather Bureau station at which continuous observations have been made.

The total concentration at a specific receptor r, $\overline{\chi}_r$, for a given pollutant is

$$\overline{\chi}_r = \sum_s \chi_{rs}, \tag{6}$$

where

χ_{rs} = the average estimated concentration at receptor r from source s, as given by Equation (5).

Using the calibration constants and background concentration values, the total calibrated mean concentration value at each receptor, $\overline{X}'_r$, (for each pollutant) is now given by,

$$\overline{X}'_r = A + B\overline{X}_r + \overline{X}_{BG}. \tag{7}$$

The values of σ_z (x,S) used in the program are those of Pasquill [1961] and Gifford [1961]. For computation these are represented in the form;

$$\sigma_z = ax^b + c \tag{8}$$

where

> a, b and c values are constants for each stability class, as shown in Table 4-2
>
> No a, b and c values are stated for S = 5 in Table A-1.

Stability class S = 5 is associated with nighttime, surface inversion conditions, and the σ_z values for this case are the smallest normally used. However, because of the thermal and mechanical influences of urban areas, the lowest part of the typical urban atmosphere is less stable than its rural counterpart. Since the Atmospheric Pollutant Concentration Program is intended for use in urban regions, the σ_z values for S = 4 are always used when the meteorological criteria indicate S = 5.

The minimum value of x used in calculating σ_z is 100 meters. If x <100 meters, x is set equal to 100 meters prior to the σ_z calculation.

TABLE A-1

COEFFICIENTS FOR σ_z CALCULATION

Stability Class (S)		a	b	c
1 ~ Very Unstable		.001	1.890	9.6
2 ~ Moderately Unstable		.048	1.110	2.0
3 ~ Slightly Unstable		.119	.915	0.0
4 ~ Neutral	x > 1000 meters	2.610	.450	-25.5
	x ≤ 1000 meters	.187	.755	- 1.4

The mixing layer height L, has a marked diurnal, daily and seasonal variation. However, since it is impractical to account for all these variations, a procedure reflecting only major changes is used in the model. The procedure determines mixing height by modifying the average afternoon mixing height values, as tabulated by Holzworth [1964], according to the stability class being considered. Stability classes S = 1, 2 and 3 are afternoon conditions, with S = 1 corresponding to very unstable conditions. When S = 1, the value of L is assumed to be 50% greater than the climatological value tabulated by Holzworth; when S = 2 or 3, the climatological value is adopted. According to Turner's criteria, S = 5 can occur only when night-time ground-based inversion conditions exist. Since a shallow layer of neutral or weak lapse conditions has been found to occur over urban areas (even with strong nocturnal surface inversions in the surrounding rural area), a mixing height of L = 100 meters is adopted for stability class S = 5, when this class is indicated by the objective criteria. The 100-meter value is based upon observations of Clarke [1969]. Stability class S = 4 is a neutral stability condition which occurs either with high wind speeds or with cloudy conditions. To find the mixing height for the transition period between day and night, the afternoon mixing height values are averaged with the 100 meter night time mixing height for 40 percent of the class S = 4 occurrences. The remaining 60 percent of the class utilizes the climatological value.

The effective stack height, h, appearing in Equation (3), is defined as the height of the plume centerline when it becomes horizontal. Thus $h = h^* + \Delta h$, where h^* is the physical stack height and Δh is the plume rise. The effective stack height does not appear in Equation (4) because the height of emission is immaterial after the pollutant is uniformally mixed in the interval.

The plume rise equation used in the program (when actual point sources are being considered) is due to Holland [1953], and is given by

$$\Delta h = \frac{V_s d}{u} \left[1.5 + 2.68 \cdot 10^{-3} P \left(\frac{T_s - T_a}{T_s} \right) d \right] \qquad (9)$$

where:

V_s = stack gas-exit velocity (meters/sec)

d = stack exit diameter (meters)

u = mean wind speed (meters/sec)

P = atmospheric pressure (mb)

T_s = stack gas-exit temperature (°K)

T_a = ambient air temperature (°K)

Since this equation is appropriate for the neutral stability condition, it must be modified when applied over a range of stability conditions. The following modification is used to allow for a range of from 1.3 Δh, for very unstable conditions, to Δh for neutral stability.

$$h = h^* + \Delta h(1.4 - 0.1S) \tag{10}$$

For some point sources (e.g., power plants with tall stacks) when the mixing height is low the effective emission height will be above the mixing height. Based on the assumption that the plume will not disperse downward through the stable layer, these cases are identified and eliminated from consideration by the program. For area sources an average effective height of emission must be estimated.

The program computes area source contributions by converting the area sources to equivalent, or "virtual," point sources. In the conversion process, both the downwind distance and source strength are dependent on the particular source-receptor configuration.

If the total emission is assumed to be concentrated at the center of an area source, concentrations downwind tend to be overcalculated, especially for nearby receptors. Since uniform spread of the plume across the sector is assumed, it is logical to proceed a step further and assume a virtual point source at such a distance upwind that the 22.5-degree sector used subtends the area width. This concept is illustrated in Figure A-3. Here the program would use x instead of x_p as the source-receptor downwind distance in Equation (3) or (4). The vertical spread, as measured by σ_z, is still calculated using x_p, the actual downwind distance.

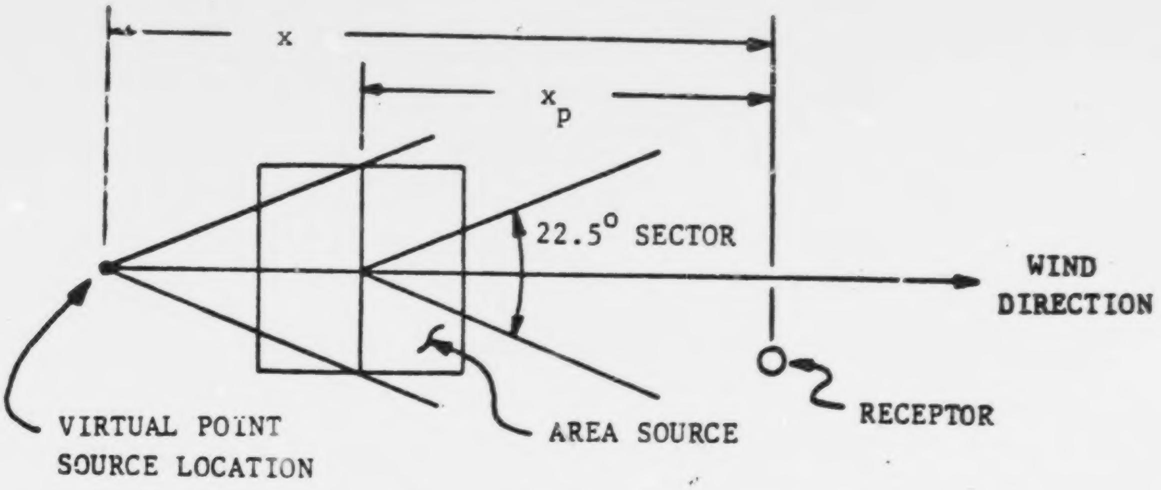

Figure A-3. Virtual Point Source Concept.

In a similar manner, nearby receptors are affected by emissions from only a portion of the source area and, therefore, would show excessive concentration values if the total area emission value were used. To correct this, the source emission rate is multiplied by an "area utilization" factor, Q*, which is the ratio of that portion of the source area lying within a 22.5-degree sector upwind of the receptor (A') to the total area (A). For example, in Figure A-4, Receptor 1 would use the total area-emission value, Q, while Receptor 2 would use the proportional amount, QQ* = A(A'/A). Note that in this figure the virtual point source would be defined by the reduced area width, W.

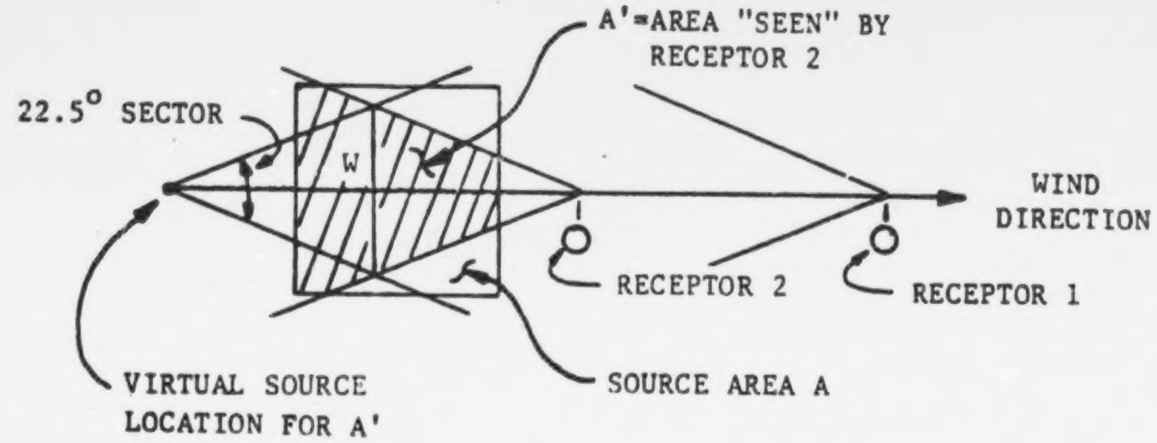
A'=AREA "SEEN" BY RECEPTOR 2
22.5° SECTOR
W
WIND DIRECTION
RECEPTOR 2
RECEPTOR 1
VIRTUAL SOURCE LOCATION FOR A'
SOURCE AREA A

Figure A-4. Area Utilization Concepts.

To account for decay of the pollutant from the atmosphere, a pollutant decay factor is applied to the concentration value χ, as determined from Equation (3) or (4). The time-based decay factor is given by exp[-.693(x/u)/(3600 T)], where T is the pollutant half-life in hours.

APPENDIX B

CONTROL COST FORMULATION

The control cost formulation presented here is taken from the Implementation Planning Program (IPP), Volume I, Chapter 5. Within the IPP framework, the control cost program utilizes data from the Source File (emission inventory data), card input to the control cost program and pre-set data in the control cost program (cost and device data).

The total annual cost resulting from the assignment of a control device to a source involves the component costs: purchase cost, installation cost, interest charges, and operating and maintenance cost. The calculations involving each of these component costs are described below.

Purchase Cost

The purchase cost of control devices depends, in general, upon the characteristics and complexity of the control device and the size of the pollution source to be controlled. In the Control Cost Program, these parameters are used to determine a basic purchase cost equation for each control device. The general form of this equation is:

$$y = a + bx + cx^2,$$

where y = purchase cost in thousands of dollars, and a, b, and c are pre-set* coefficients in the device specification. Experience has shown that the coefficient c in the above equation can be set equal to zero in most instances. Table B-1 displays the pre-set coefficients associated with each control device including in the Control Cost program. The parameter x represents the measure of the source's size, as described below.

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*The term pre-set indicates values which exist in the program but may be changed by user input.

Table B-1. Control Measure Purchase Cost Equations

Control Measure[1]		Purchase Cost Equation[2]
Wet Collector		
001	High Efficiency	$y = 2.886 + .288x$
002	Medium Efficiency	
003	Low Efficiency	$y = 1.257 + .145x$
Mechanical (Centrifugal)		
007	High Efficiency	$y = 2.413 + .197x$
008	Medium Efficiency	$y = 1.507 + .157x$
009	Low Efficiency	$y = .244 + .099x$
Electrostatic Precipitators		
010	High Efficiency	$y = 42.413 + .623x$
011	Medium Efficiency	$y = 31.243 + .441x$
012	Low Efficiency	$y = 19.695 + .318x$
Gas Scrubber		
013		$y = 3.175 + .251x$
Mist Eliminator		
014	High Velocity	$y = 2.658 + .325x$
015	Low Velocity	$y = 1.772 + .217x$
Fabric Filters		
016	High Temperature Type	$y = 1.448 + .838x$
017	Medium Temperature Type	$y = 3.478 + .448x$
018	Low Temperature Type	$y = 2.658 + .325x$

---

[1] See Table 3-1 for device descriptions.

[2] Cost Functions; $y = 10^3$ dollars, $x = 10^3$ ACFM unless noted otherwise.

Table B-1. Control Measure Purchase Cost Equations
(Contined)

	Control Measure	Purchase Cost Equation[1]
Increased Combustion Efficiency (Afterburner)		
019	Catalytic Combustion	$y = 7.550 + 1.515x$
020	Catalytic with Heat Exchanger[2]	$y = 7.550 + 1.515x$
021	Direct Flame Combustion	$y = 5.713 + 1.174x$
022	Direct Flame with Heat Exchanger[2]	$y = 5.713 + 1.174x$
Flue Gas Desulfurization[3]		
039	Catalytic Oxidation	$\log_{10} y = -12.41 + 1.67 \log_{10} x$
041	Limestone Injection (dry)	$y = 9.95 \cdot 10^{-7} x - 6.03 \cdot 10^{-17} x^2$
042	Limestone Injection (wet)[4]	$+ 9.572 \cdot 10^{-8} sx - 4.16 \cdot 10^{-18} sx^2$
By-Product Manufacture[5]		
043	Sulfuric Acid Plant (Contact Process)	$\log_{10} y = a + bx$
044	Sulfuric Acid Plant (Double Contact)	
045	Sulfur Plant	

---

[1] Cost Functions; $y = 10^3$ Dollars, $x = 10^3$ ACFM unless noted otherwise.

[2] Heat exchangers are considered accessory equipment and their costs are included under installation costs.

[3] The "x" terms in these equations are the rated capacity of the source (BTU/hr); $y = 10^3$ dollars.

[4] In practice, this process only applies to coal. The parameter "s" appearing in the cost equation is the sulfur content in percent by weight (i.e., $0 \leq s \leq 100$).

[5] See page B-5 item (f) for parameter definitions.

(a) Devices 001, 002, 003, 013

For these devices, x is exhaust gas volume in thousands of ACFM. Since a temperature change occurs in these wet collection devices, a new exhaust volume based on the original gas volume is computed (for use in the O&M calculations) as follows:

$$T_n = 294 + .097\ (T_o - 294)$$

where T_n = new exit temperature (°K)

T_o = exit temperature as obtained from the Source File (°K)

then the new exhaust gas volume, V, is given by

$$V = V_o(T_n/T_o)$$

where V_o = exhaust gas volume as obtained from the Source File (ACFM)

(b) Devices 004-012 and 014-018

The parameter x is the exhaust gas volume in thousands of ACFM as obtained from the Source File with no corrections applied. If, however, the exit temperature is greater than 532°K (500°F), gas cooling must be utilized prior to the application of devices 010-012 and 016-018. As a result, the purchase (and O&M) costs for these devices use an adjusted ACFM value, calculated as follows:

$$V = V_o\ (526.2 + .023\ T_o)/T_o$$

$$T_n = 500°K$$

The cost associated with the cooling requirement is determined by the following equations and is added to the O&M costs.

If exhaust gas volume is greater than or equal to 2000 ACFM but less than 6800 ACFM,

$$\text{Cost (\$)} = 1131.7 \left[e^{[.436\ \ln\ (V_o 1000)]} \right] + 124 + .07185\ V$$
$$+ V_o \left[\left(.0003225 + .000016286\ \frac{.24T_o - 71.2}{T_o}\right) H + \frac{.0000019\ (.24T - 71.26)\ H}{T_o} + .04 \right]$$

If exhaust gas volume is greater than or equal to 6800 ACFM but less than 100,000 ACFM

$$\text{Cost (\$)} = 720.17 \left[e^{[.668 \ln (V_o/1000)]} \right] + 124 + .07185\ V$$
$$+ V_o\ [(.0003225 + .000016286\ \frac{.24T_o - 71.2}{T_o}\ )\ H$$
$$+ \frac{.0000019\ (.24T - 71.2)}{T}\ H + .04]$$

where

V_o = exahust gas volume (ACFM)

V = volume of cooled gas to control device (ACFM @ 500°F)

$= V_o\ [526.2 + .023T_o]/T_o$

H = operating hours per year

$\approx 365 \cdot (\text{number of shifts/day}) \cdot 8$

T_o = exhaust gas temperature (°K)

If the gas volume is less than 2000 ACFM, the program will not apply the device being considered and will go on to the next assigned device.

If the gas volume is greater than 100,000 ACFM, the program will divide the ACFM value into equal parts, each of which is less than 100,000 ACFM. The gas cooling data will then be calculated using the procedure described above. The resulting cost and cooled exhaust gas volume is then multiplied by the number of equal parts to produce the total values for the device.

The costs calculated above combine purchase, installation, and operating costs for the gas cooling measure (assumed to be of the water spray type) and are on an annualized basis. The new exhaust gas volume (V) and new exhaust gas temperature (532°K) become the new source-device characteristics.

(c) Devices 019-022

The parameter x in these purchase price equations is the output exhaust gas volume. As these devices (afterburners) produce a change in the exit temperature, the output ACFM made be determined prior to purchase price calculations. The new exit temperature (T_n) is given by

$$T_n = T_o + t$$

where T_o = existing exit temperature (°K)

t = 288 for device 019
139 for device 020
556 for device 021
222 for device 022

then the new (output) ACFM is determined from

$$V = V_o(T_n/T_o)$$

(d) Device 039

For this device, x is the logarithm (base 10) of the rated capacity of the plant (BTU/hr.), and y is the logarithm (base 10) of the purchase cost (10^3 $).

(e) Devices 041-042

For these devices, x is the rated capacity of the plant (BTU/hr.) as obtained from the Source File, and y = 10^3 dollars.

(f) Devices 043-045

For these devices, x is the logarithm (base 10) of the amount of sulfur in the exhaust gas in tons/day, calculated as follows:

$$x = \log_{10} (E_s/2)$$

where E_s = annual average SO_2 emission rate as obtained from the Source File (tons/day).

The price coefficient "a" is determined by the program on the basis of the device and the percent by volume of sulfur dioxide in the exhaust gas. This percent is calculated using the following formula:

$$P = 18.48E_s/(V \text{ shifts})$$

where E_s = annual sulfur dioxide emission rate as obtained from the Source File (tons/day)

T = exit temperature as obtained from the Source File (°K)

V = exhaust gas volume as obtained from the Source File (ACFM)

Shifts = number of 8-hour shifts per day from the Source File

P = percent sulfur dioxide by volume in the exhaust gas

The quantity "a" (to be used in the cost equation) is then determined as follows:

	Device 043	Device 044
$0 \le P \le 3.0$	$a = -0.8218$	$a = -0.7426$
$3.0 < P \le 6.0$	$a = -1.0647$	$a = -0.9855$
$6.0 < P \le 10.0$	$a = -1.2937$	$a = -1.2145$
$P > 10.0$	$a = -1.3449$	$a = -1.2657$

	Device 045
$0 \le P \le 5.0$	$a = -0.5779$
$5.0 < P \le 7.0$	$a = -0.7069$
$P > 7.0$	$a = -0.7629$

In these cases the "y" value, produced by the cost equation, is the logarithm (base 10) of the purchase cost in millions of dollars.

In summary, the cost equation for devices 043, 044, and 045 is:

$$\log_{10} y \, 10^{-6} = a + b \log_{10}(E_s/2)$$

where y = purchase cost

a = number determined by device type and percent SO_2 in exhaust gas.

b = user input Manufacturer's Price Coefficient No. 2.

A final test is made to eliminate very low efficiency devices (based on purchase cost). If the purchase cost is less than $1.0 \cdot 10^6$ for device 043, $1.2 \cdot 10^6$ for device 044; or $2.5 \cdot 10^6$ for device 045, the device is not applied.

When the corrosive gas streams from acid manufacturing facilities (SIC 2819, Process Codes 01 or 02) are controlled, more expensive control device construction materials must be used. For these cases the Control Cost Program utilizes the following factors to increase the device purchase price:

If exit temperature < 330°F, multiply purchase cost by 1.7.
If exit temperature $\ge$ 330°F, multiply purchase cost by 5.0.

Installation Cost

The cost of installing a control device on a particular source is calculated on the basis of an installation cost factor. This factor is expressed as a percentage (decimal equivalent) of the purchase price and is a pre-set item for each control device. The program sums purchase cost and installation charge to determine the total installed cost for each source-device combination.

For some control device installations, however, extensive modifications of the source are required and it is not possible to identify a purchase cost figure independent of the installation charge. For these devices, the total installed cost is estimated by the purchase price equations described under Purchase Cost. No additional factor is required in these cases to account for installation at a source site. Devices in this category are the flue gas desulfurization units (039, 041, 042) and by-product manufacturing facilities (043, 044, 045).

Annual Capital Charge

After the total installed cost (purchase plus installation) of a device has been determined, an annualized capital charge is calculated, based on the pre-set rated life of the control device and the user input prevailing interest rate. Therefore, the annual cost comprises both depreciation of the initial total investment (installed cost from Installation Cost) and the interest costs.

The particular accounting technique employed here is called the Capital Recovery Factor (C.R.F.). The use of the C.R.F. allows the write-off of the initial investment to be divided into a uniform series of end-of-year payments.

The C.R.F. multipled by the initial investment cost (debt) determines the uniform end-of-year payments necessary to repay the debt in "N" years (the rated life of the device) with an interest rate "i" (decimal equivalent) The C.R.F. is calculated by the following relation:

$$\text{C.R.F.} = \frac{i(1 + i)^N}{(1 + i)^N - 1}$$

The annual capital charge is then computed to be the product of the total installed cost and the C.R.F. value.

In practice, the capital recovery concept operates as follows:

(1) Payments are made at the end of each year in the amount determined by multiplying the capital recovery factor by the initial debt.

(2) Interest payments are made to the bondholders at the end of each year in the amount determined by multiplying the interest rate by the initial debt.

(3) The difference between the equal annual payments and the interest payments to the bondholders is placed into a depreciation account where it is assumed to draw interest at the same rate paid to the bondholders.

The total yearly cost to the source for controlling pollution by means of a specified device is then the sum of the annual capital charge and the annualized operating and maintenance expense discussed in the next subsection.

Operating and Maintenance Expense

Operating and maintenance (O&M) expenses are usually a major portion of the annualized control device cost. The factors which must be considered in determining the annual O&M cost of a particular source-device combination consist of: the amount of power (calculated as electrical power) necessary to maintain the effluent gas flow through the control device, the quantity of labor required, the cost of liquid or additional fuel used by the device, and the cost or credit resulting from disposal of the collected pollutant. These factors are used in the following equations to determine the O&M cost for each type of control device pre-set in the program.

For control devices 001 through 022, a single equation is used to compute the annual O&M cost:

$$O\&M = AB + CD + EF + GI + JK + LM,$$

where A = electricity quantity (kwhr/yr) (a)*
B = electricity cost ($/kwhr) (input as regional data)

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* The letters refer to the following items which describe the computation of these data elements.

C = water quantity (gal/yr)	(b)
D = water cost ($/gal)	(input as regional data)
E = chemical quantity (ton/yr)	(c)
F = chemical cost ($/ton)	(pre-set as device data)
G = fuel quantity (cu.ft./yr)	(d)
I = fuel cost (S/cu.ft.)	(natural gas value, input as regional data)
J = disposal quantity (ton/yr)	(e)
K = disposal cost ($/ton)	(pre-set as device data)
L = labor quantity (hr/yr)	(f)
M = labor cost ($/hr)	(input as regional data)

The computation of these data elements are described below. In each case for which the exhaust gas volume is required, the new computed value should be be used [as determined under Purchase Cost, items (a), (b), and (c)].

(a) Electricity Quantity (kwhr/yr) = $(1.955\cdot 10^{-4})pVH$

where p = pressure drop (in H_2O)

V = new exhaust gas volume (ACFM)

H = operating hours (hr/yr)

If the device is one of the electrostatic precipitators (010, 011, 012), the following quantities are added to the electricity quantity:

Device 010, add $(0.34\ 10^{-3})$ VH

Device 011, add $(0.26\ 10^{-3})$ VH

Device 012, add $(0.19\ 10^{-3})$ VH

(b) Liquid Quantity (gal/yr) = $(3.0\ 10^{-2})$ VH

The liquid quantity is only computed for wet devices (001, 002, 003, 013). For these cases the exhaust gas volume (V) will always be the new computed volume.

(c) Chemical Quantity (ton/yr) = $P_s H/{*}8\cdot$shifts

where P_s = amount of SO_2 removed by the device P_s is calculated as SO_2 emission rate times applied efficiency (see Table B-2) $H/(8\cdot$shifts) gives the operations time per year.

(d) Fuel Quantity = fVH

where f = 0.490, if device 019
0.245, if device 020
1.000, if device 021

Table B-2. Existing Device Correction Factors

Existing Efficiency	Correction Factor		
	Wet Scrubber (001,002,003,013)	Dry Cyclone (007,008,009)	Electrostatic Precipitator (010,011,012)
> 0 and ≤40	1.0	1.0	1.0
>40 and ≤60	1.1	1.3	1.0
>60 and ≤65	1.2	1.8	1.1
>65 and ≤70	1.3	2.3	1.2
>70 and ≤75	1.5	2.7	1.3
>75 and ≤80	1.8	3.2	1.6
>80 and ≤83	2.2	3.8	2.0
>83 and ≤86	2.6	4.4	2.5
>86 and ≤89	3.1	5.1	2.9
>89 and ≤91	3.5	5.8	3.4
>91 and ≤93	4.1	6.6	3.9
>93 and ≤95	4.7	7.6	4.4
>95 and ≤97	5.5	9.0	5.4
>97 and ≤99	7.3	11.0	7.5
>99 and ≤100	10.0	12.0	11.0

Applied Eff. = 1. - (1. - Rated Eff.) (Correction Factor)

0.404, if device 022

0.000, all other devices

V is the output (i.e., new) ACFM

It should be noted that additional fuel is only used for the catalytic and direct flame afterburners. The program assumes that the additional fuel is natural gas.

(e) Disposal Quantity - Emission rate for pollutant in question (tons/day) times new device efficiency (after adjustment) for same pollutant times days of operation per year.

This computation is performed for each of the pollutants.

(f) Labor Quantity = LH

Where H = operating time (hr/yr)

L = labor (labor hours/operation hours)

There are four, pre-set, labor values which relate to the source size being controlled (small, medium, large, and extra large). Source size is measured by V, actual cubic feet of exhaust gas per minute (as corrected). The program selects the appropriate value as follows:

Use the "small" value for	$V \le 40{,}000$
Use the "medium" value for	$40{,}000 < V \le 250{,}000$
Use the "large" value for	$250{,}000 < V \le 1{,}000{,}000$
Use the "extra large" value for	$V > 1{,}000{,}000$

For any particular control device, only some of the terms in the above equation will be non-zero. An electrostatic precipitator, for instance, will not use liquid, chemicals, or additional fuel. The quantity JK however, will always be calculated.

Operating and maintenance costs for the remaining control devices cannot be estimated by the above calculations. These devices are generally more complex (involving sulfur oxide removal), and separate equations have been developed to compute their O&M expenses. These equations are based on manufacturers' specifications and operating experience reported in the literature.

For the three flue gas desulfurization measures considered, the following calculations of operating cost are used.

Device 039 - Catalytic Oxidation

$O\&M = 0.05 \cdot (\text{total installed cost}) + AB + JK$

Where A, B, J, and K are as defined above.

Device 041 - Dry Limestone

$O\&M = 365\ P_c\ (0.17 + 7.0\ SC_c) + 25{,}000$

Device 042 - Wet Limestone

$O\&M = 365\ P_c\ (0.196 + 3.82\ SC_c) + 130{,}000$

where P_c = coal burned in ton/day (Source File)

S = coal sulfur content, decimal (Source File)

C_c = chemical cost in $/ton (input as device data)

The O&M costs associated with the use of sulfuric acid or sulfur by-product manufacturing as a pollutant control measure (devices 043, 044, and 045) are computed from the following equation:

$O\&M = JK - (\text{Purchase Cost})/(\text{Rated Life}) + y$

where, for each device:

J = disposal quantity, as calculated in item (e) above.

K = input disposal cost

Purchase Cost = value computed on page 60, item (f)

Rated Life = input as device data

y = value as calculated below. The variable P used in these computations is the percentage concentration of sulfur dioxide, by volume, in the exhaust gas as given on Page 60 , item (f).

Devices 043,044-Sulfuric Acid Plant-Single Contact and Double Contact Process

$$\log_{10}y = 0.75 \log_{10}x + a$$

where y = annual cost (in 10^3 \$)

x = sulfur emission in tons/day

if $0 \leq P < 3.0$, then a = 1.6903

$3.0 \leq P < 6.0$, then a = 1.4445

$6.0 \leq P < 10.0$, then a = 1.2076

$P > 10.0$, then a = 1.721

Device 045 - Sulfur Plant

$$\log_{10}y = 0.81 \log_{10}x + a$$

where y = annual cost (in 10^6 \$)

x = sulfur emission (above)

if $0 \leq P < 5.0$, then a = -1.210

$5.0 \leq P < 7.0$, then a = -1.375

$P \geq 7.0$, then a = -1.435

The total annual device cost, output by the program, is then the annual capital cost (defined under Annual Capital Charge) plus the O&M cost and, if applicable, the gas cooling cost.

APPENDIX C

EFFECTIVE STACK HEIGHT PARAMETER RANGES

Since the sensitivity of each of the effective stack height parameters is dependent on the nominal set of parameters chosen, a realistic nominal set is required to properly rate the parameter sensitivity. To determine a set of nominal values, the detailed emission inventories for six previously inventoried regions were utilized (Chicago, Cincinnati, Denver, Philadelphia, St. Louis, and Washington, D.C.). Although several of these inventories were in the final checkout stage (and, therefore, subject to a limited number of changes), no attempt was made to investigate apparently spurious data. It is anticipated that the sample size was large enough that a small number of data errors would not affect the parameter trends established.

The inventory data were divided into the three categories: Power Plants, Fuel Combustion (except Power Plants), and Industrial Process. For each category the stack height (h), exit velocity (V), exit diameter (D), and exit temperature (T) were plotted versus plant size (rated capacity for fuel burning source and ACFM for industrial process sources). Although no precise relationship could be established between the various stack parameters and source size (as to be expected for such broad source groups), the nominal values and ranges over which these parameters occurred were, in general, defined. The user should note, however, that the nominal values presented here should not be used in place of missing inventory data. These results provide only the general parameter range and a nominal set for comparison purposes. To illustrate the pitfall of using such nominal values in an inventory,the techniques of the parameter sensitivity analysis (Chapter 2.0) were used to relate the Power Plant parameter ranges to a corresponding deviation in maximum annual average pollutant concentration values.

Figures C-1 through C-4 show the plots of Power Plant stack height, exit velocity, exit diameter, and exit temperature versus rated capacity, respectively. These data were taken from 102 powerplants located throughout the six regions. In each figure, loci of parameter extremes are shown

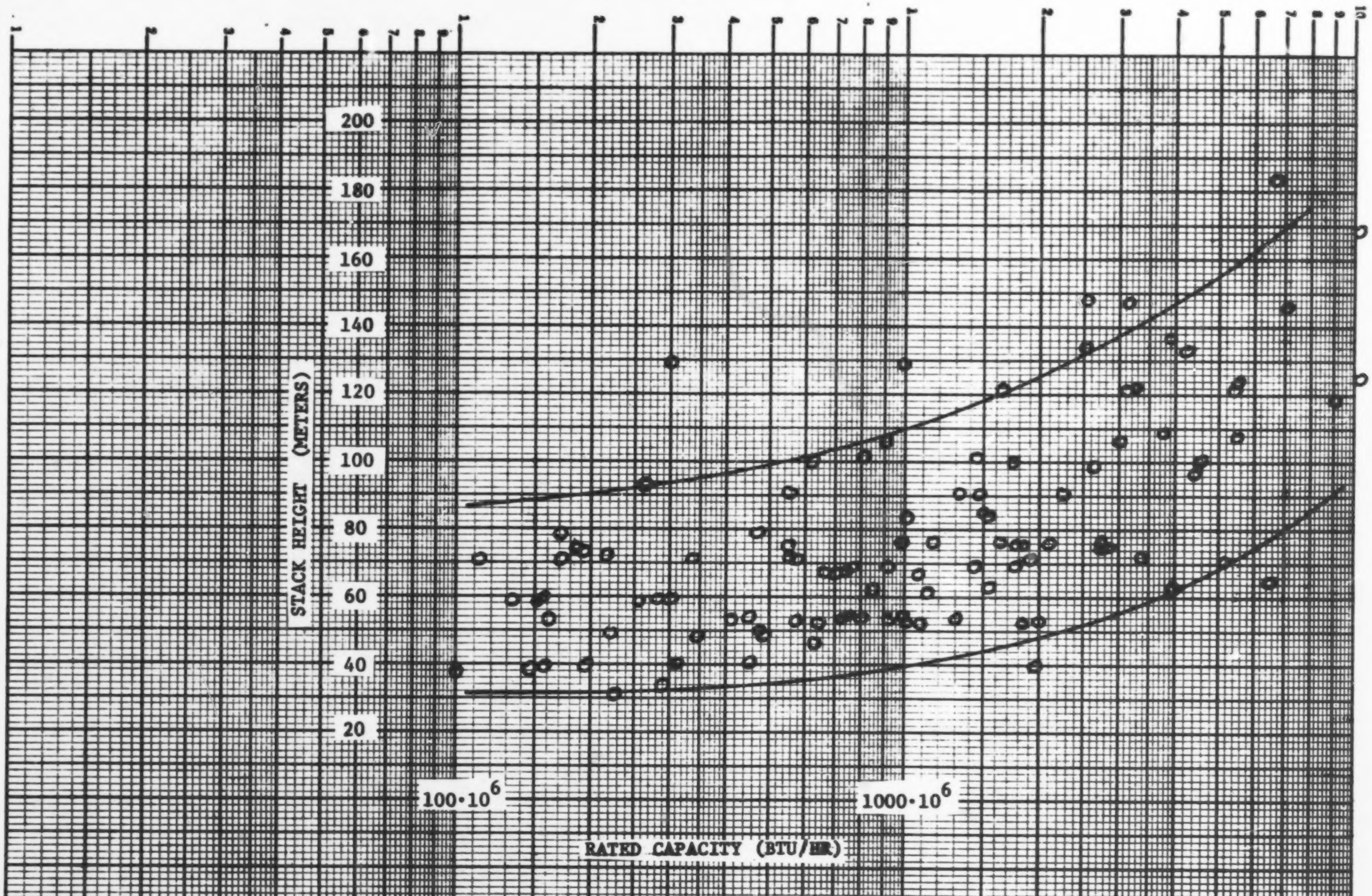

Figure C-1. Stack Height Range for Power Plants.

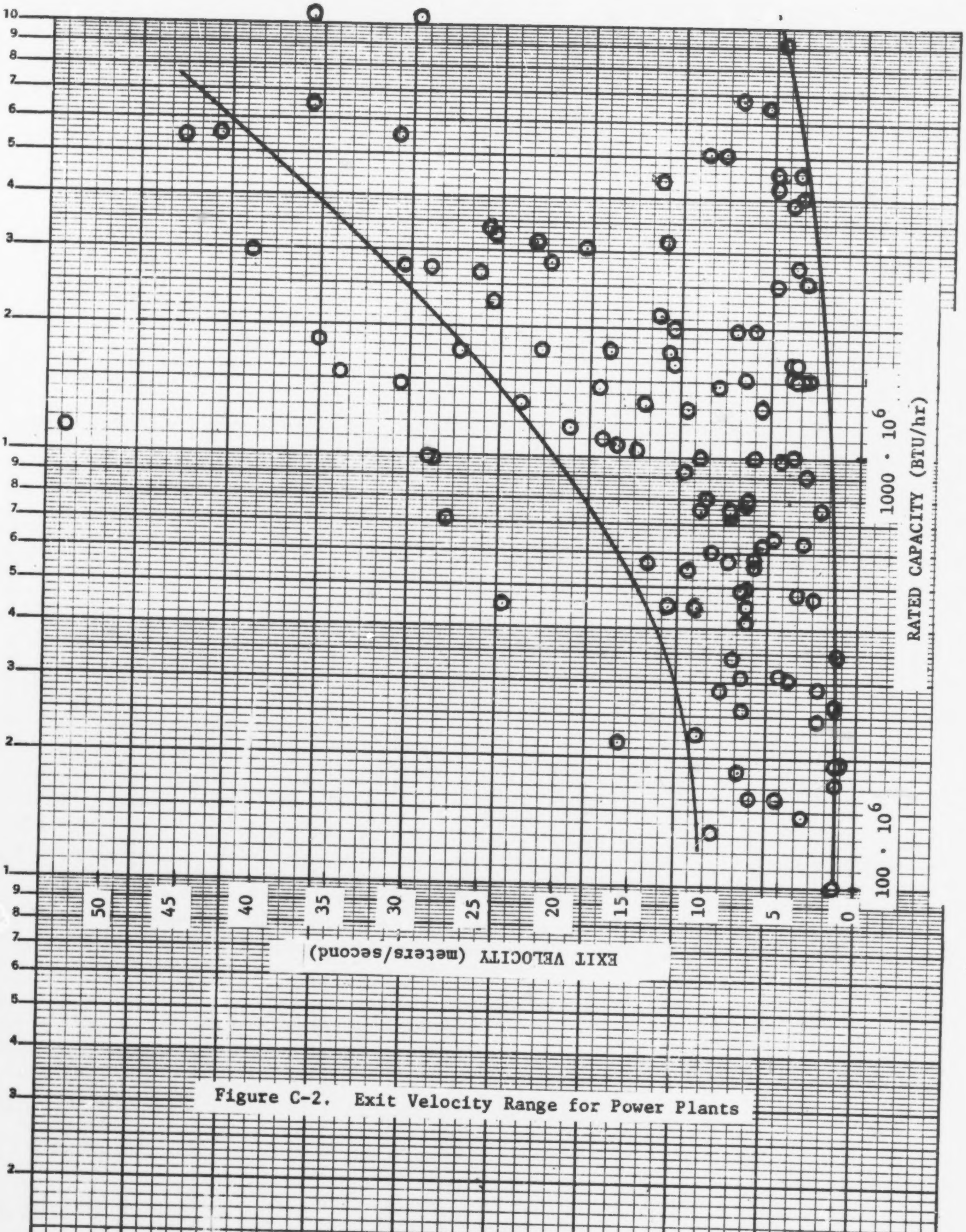

Figure C-2. Exit Velocity Range for Power Plants

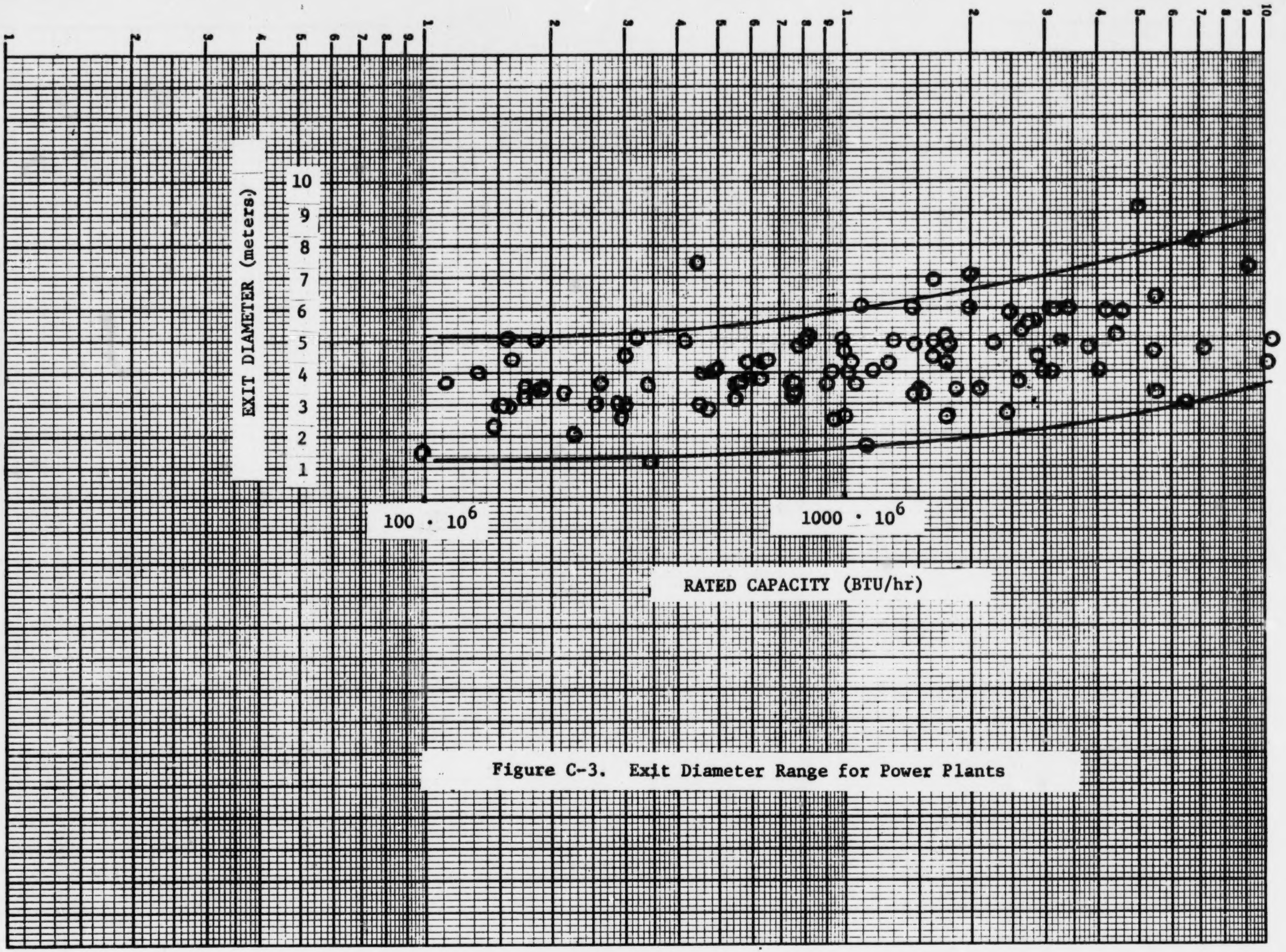

Figure C-3. Exit Diameter Range for Power Plants

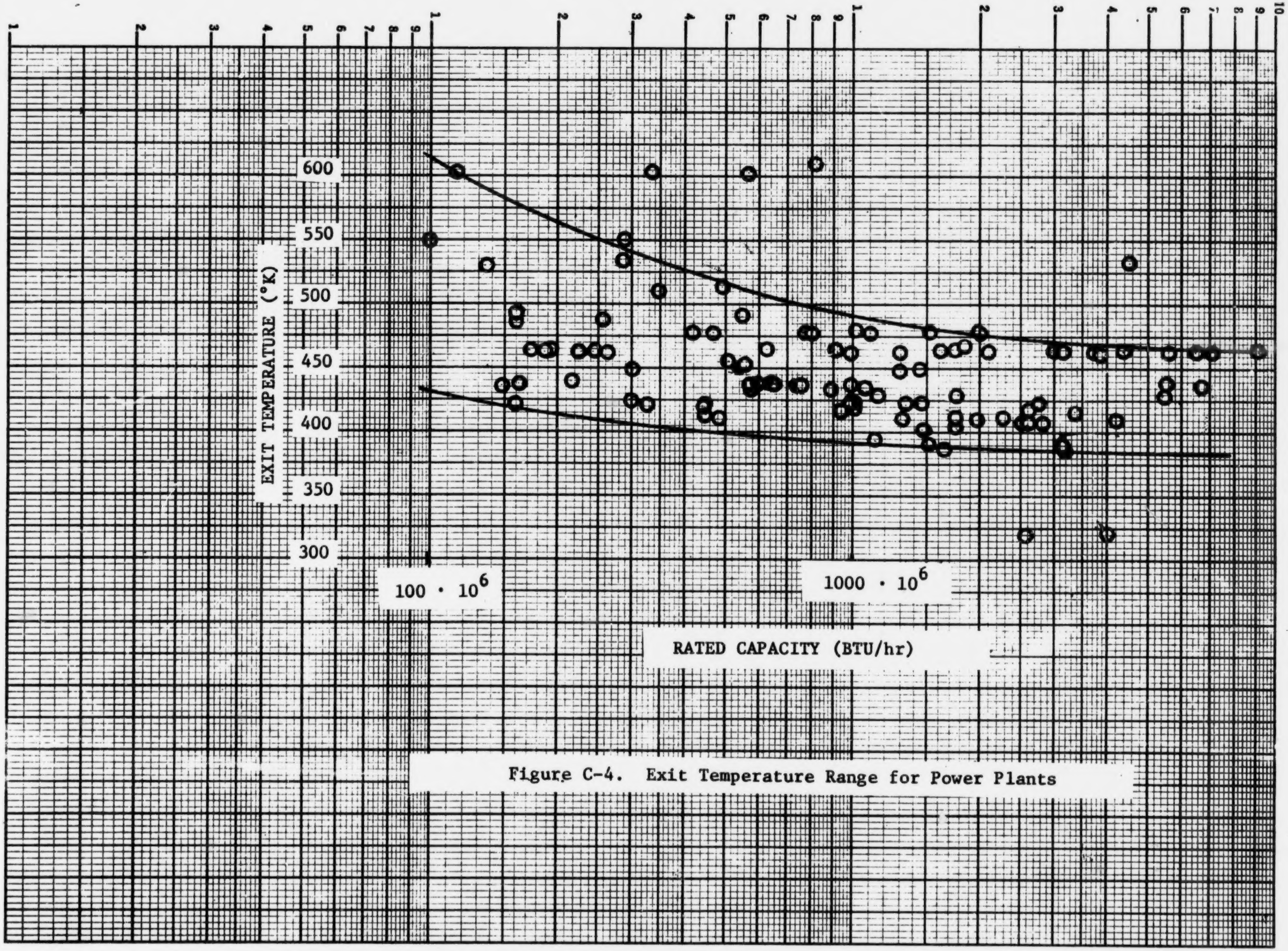

Figure C-4. Exit Temperature Range for Power Plants which include 90 percent of the data points. Table C-1 summarizes the average parameter values and their ranges for small to medium ($100*10^6$ to $600*10^6$BTU/hr), medium to large ($600*10^6$ to $2000*10^6$ BTU/hr), and large to extra large ($2000*10^6$ to $10,000*10^6$BTU/hr) power plants. Using these data to determine χ_m/χ_{m_o} [Equations (3) and (4),Chapter 2.0], for each parameter in each plant size group, shows that significant pollution concentration errors could be introduced if an average V or D value were used in place of measured (or carefully estimated) data. The maximum pollutant concentration errors that could result from use of average values for each of the stack parameters are shown in Table C-1 as "Maximum Concentration Error."

Figures C-5 and C-6 are plots of the power plant effective stack height [calculated using Equation (1)] and ACFM values versus rated capacity. The apparently narrow parameter ranges for these plots are deceptive. Using the same analysis as above, the use of an average effective stack height value from Figure C-5 could produce a maximum pollutant concentration error of 500 percent. From the control cost analysis of Chapter 3.0, the use of an average ACFM value from Figure C-6 could produce an average annual control cost error of around $100,000 for each device.

Figures C-7 through C-11 show the Fuel Combustion plots of h, V, D, T, and ACFM versus rated capacity, respectively. Figures C-12 through C-15 show the industrial process plots of h, V, D, and T versus ACFM, respectively. In each figure, loci of parameter extremes are shown.

Table C-2 contains a summary of the parameter ranges and nominal values taken from the parameter plots. The nominal values presented are, in general, median values.

Table C-1. Average Parameter Range for Powerplants

	Parameter Value					
Parameter	Small to Medium Plant	Maximum Concentration Error	Medium Large Plant	Maximum Concentration Error	Large to X-Large Plant	Maximum Concentration Error
Stack Height (meters)	60 ± 20	40%	70 ± 30	80%	110 ± 50	100%
Exit Velocity (m/sec)	7 ± 5	>400%	15 ± 14	>400%	20 ± 16	>400%
Exit Diameter (meters)	$3\frac{1}{2}$ ± 2	>400%	4 ± 2	>400%	5 ± 3	>400%
Exit Temp (°Kelvin)	480 ± 60	30%	450 ± 40	20%	440 ± 30	15%

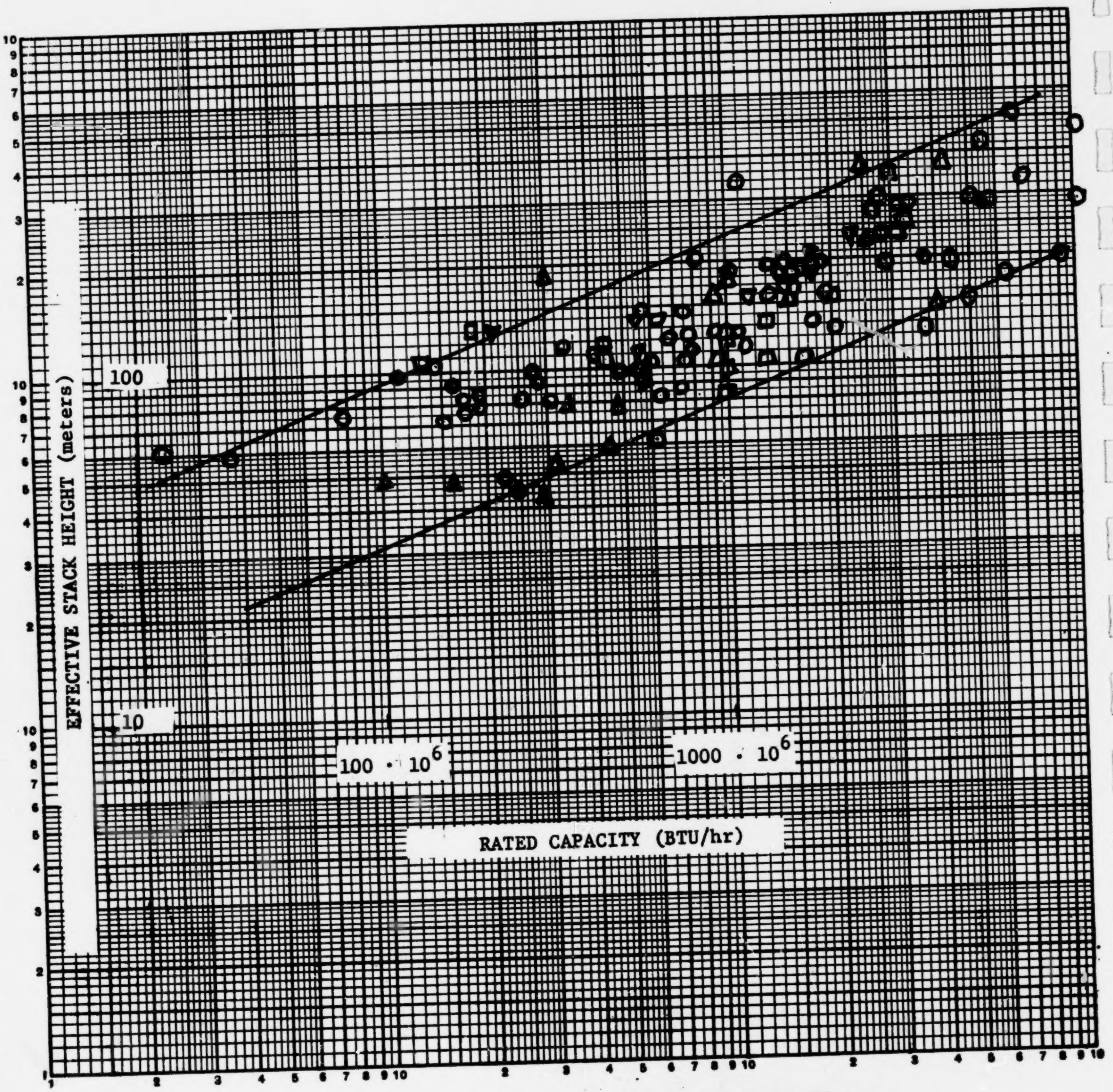

Figure C-5. Effective Stack Height Range for Power Plants

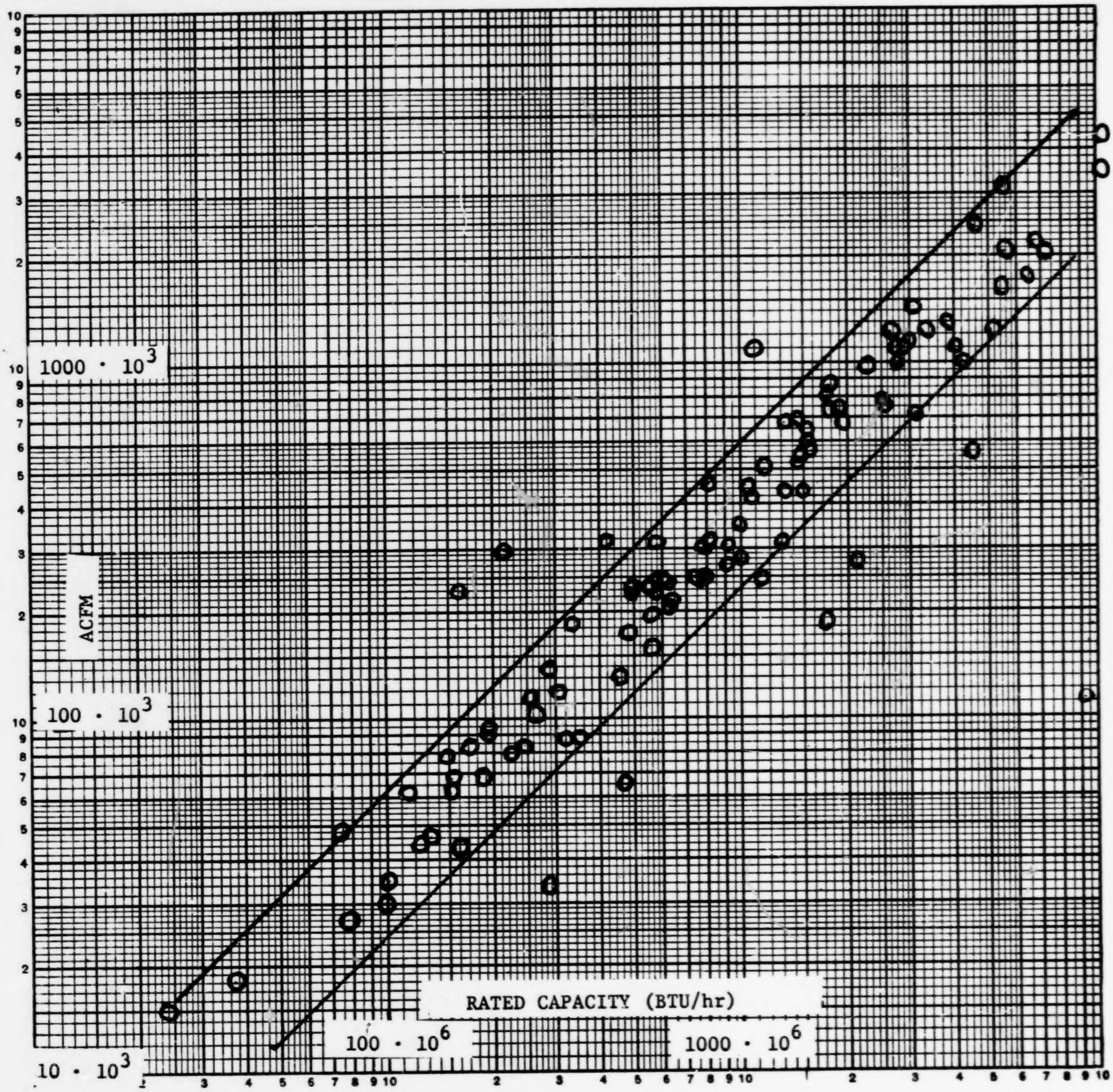

Figure C-6. ACFM Range for Power Plants

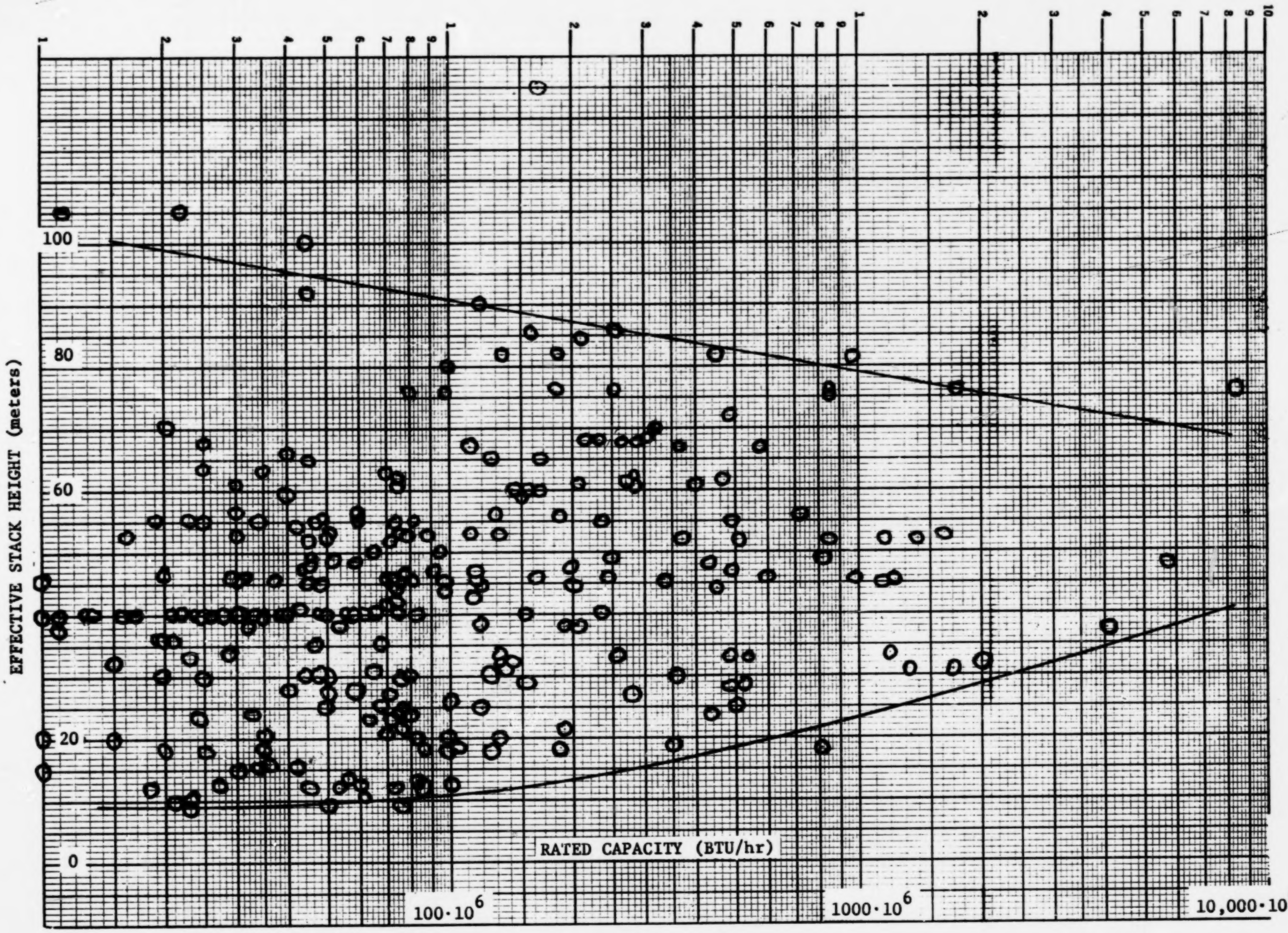

Figure C-7. Effective Stack Height Range for Fuel Combustion Sources (Excluding Power Plants)

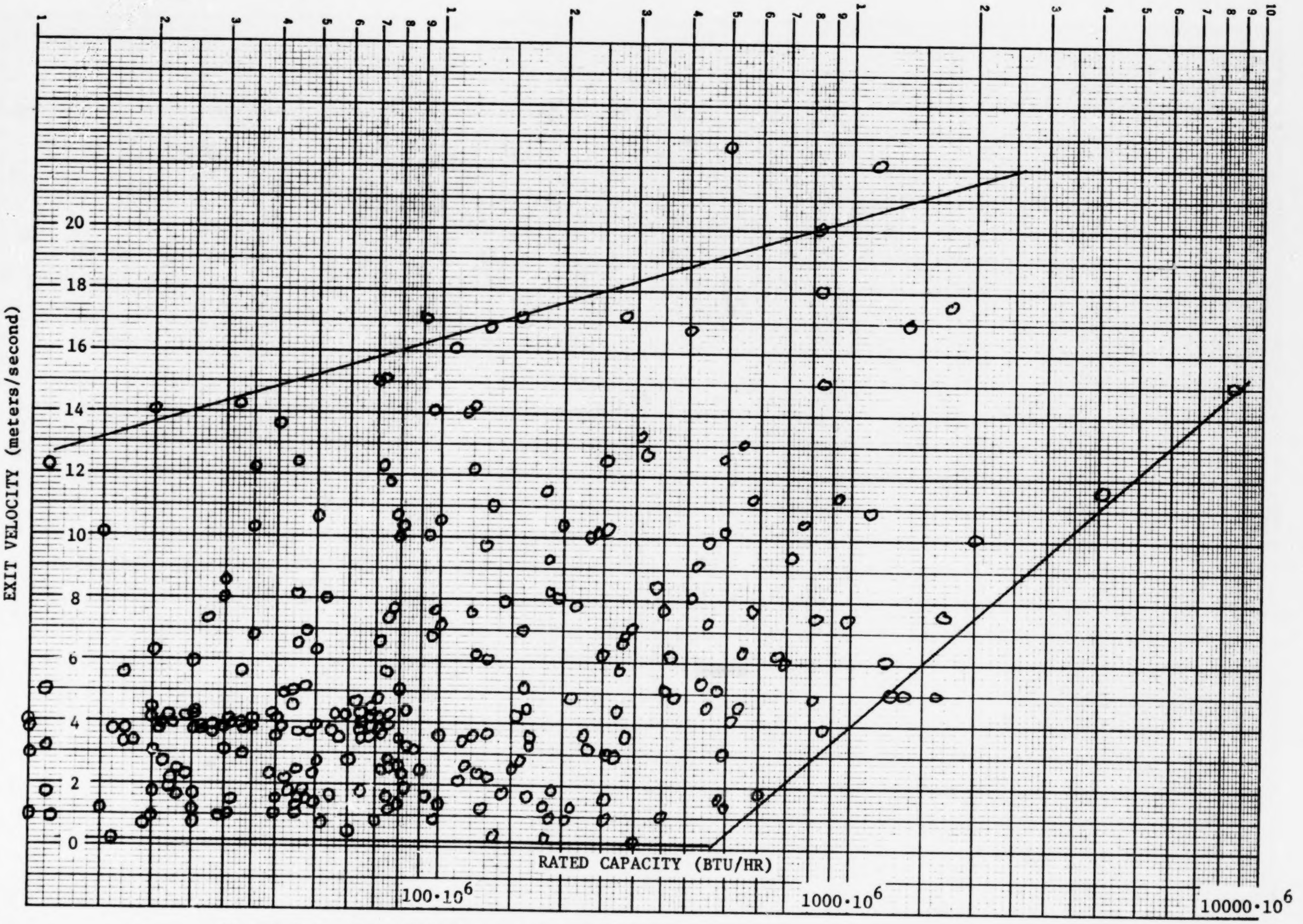

Figure C-8. Exit Velocity Range for Fuel Combustion Sources (Excluding Power Plants)

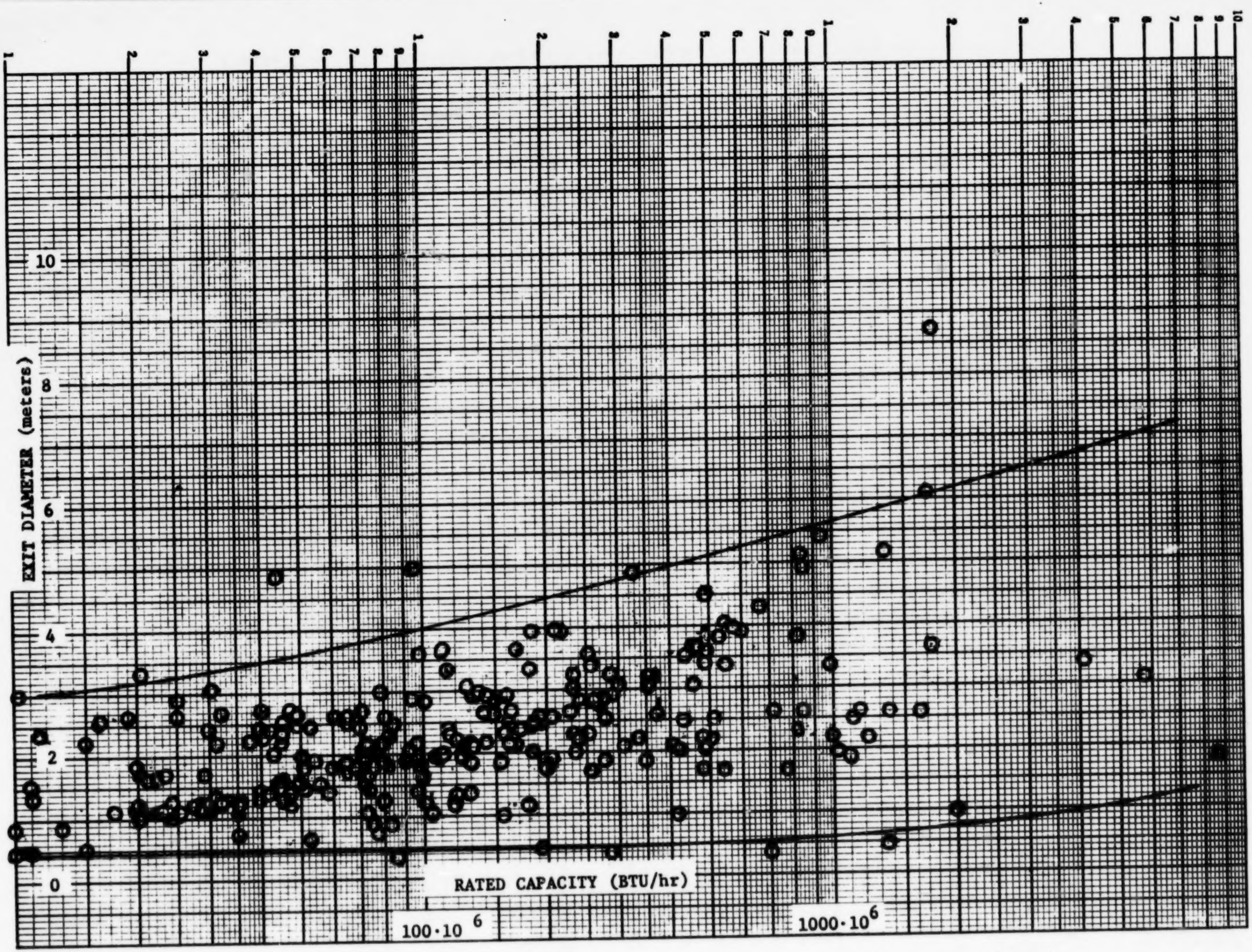

Figure C-9. Exit Diameter Range for Fuel Combustion Sources (Excluding Power Plants)

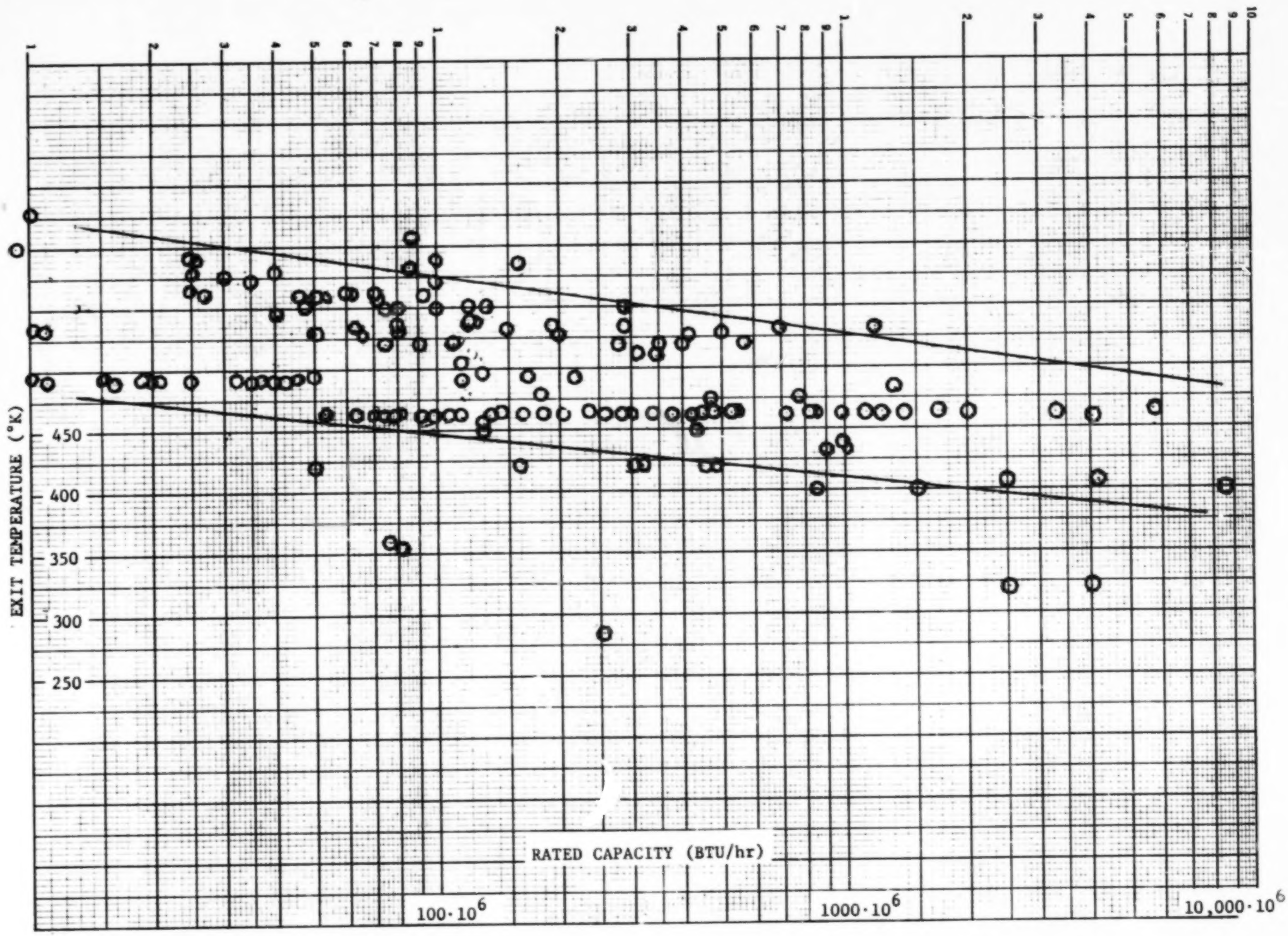

Figure C-10. Exit Temperature Range for Fuel Combustion Sources (Excluding Power Plants)

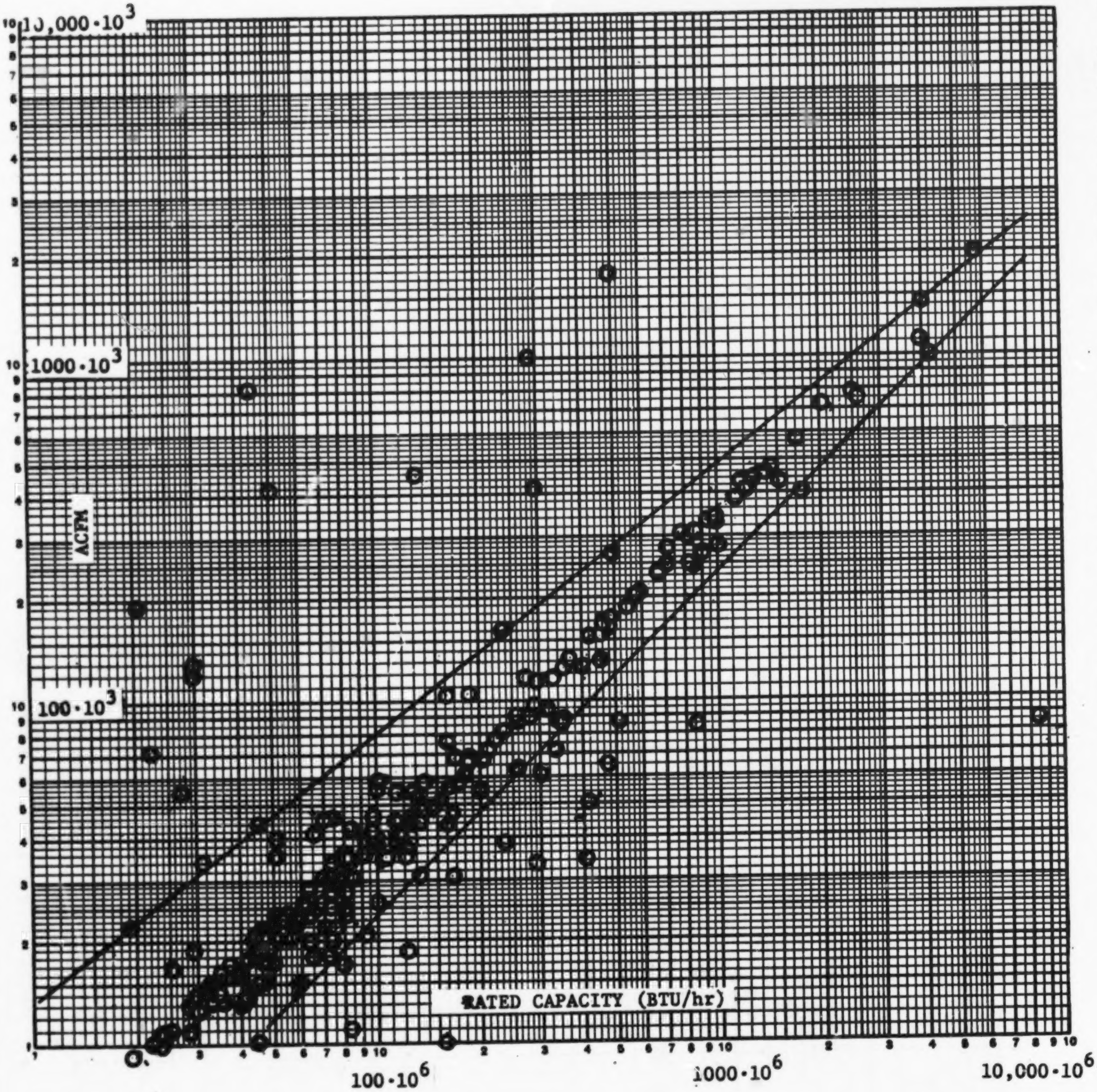

Figure C-11. ACFM Range for Fuel Combustion Source (Not Including Power Plants)

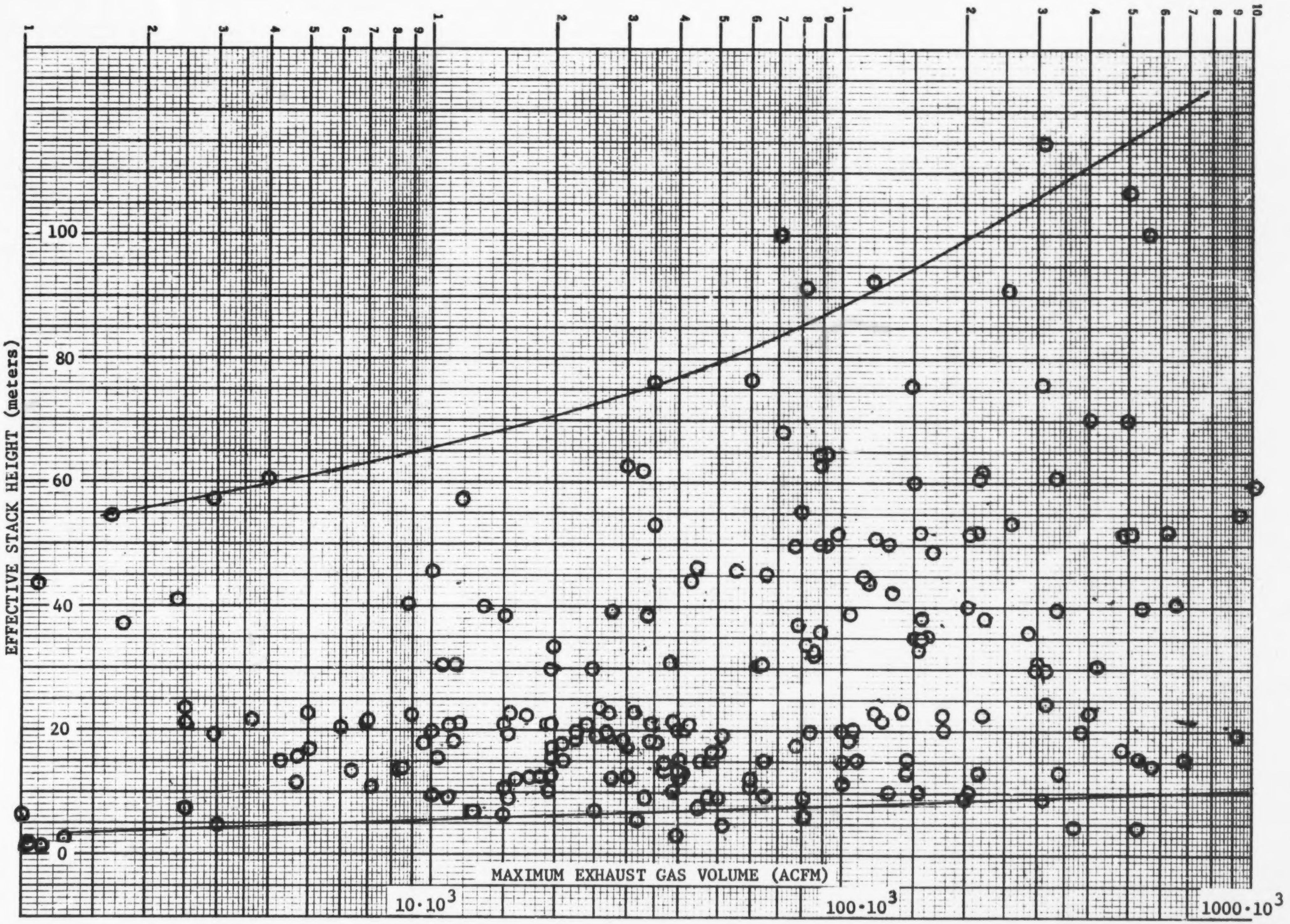

Figure C-12. Effective Stack Height Range for Industrial Process Sources

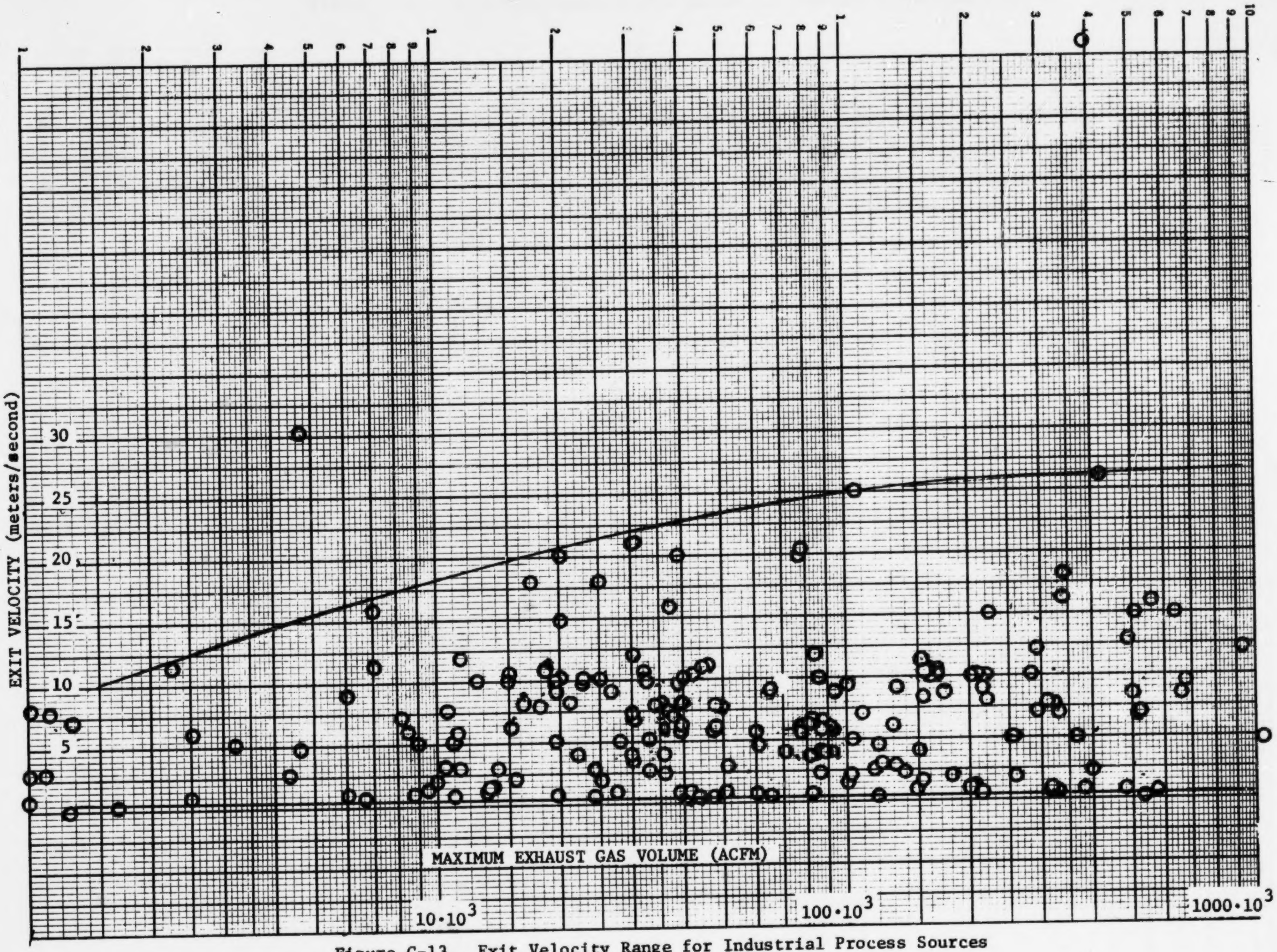

Figure C-13. Exit Velocity Range for Industrial Process Sources

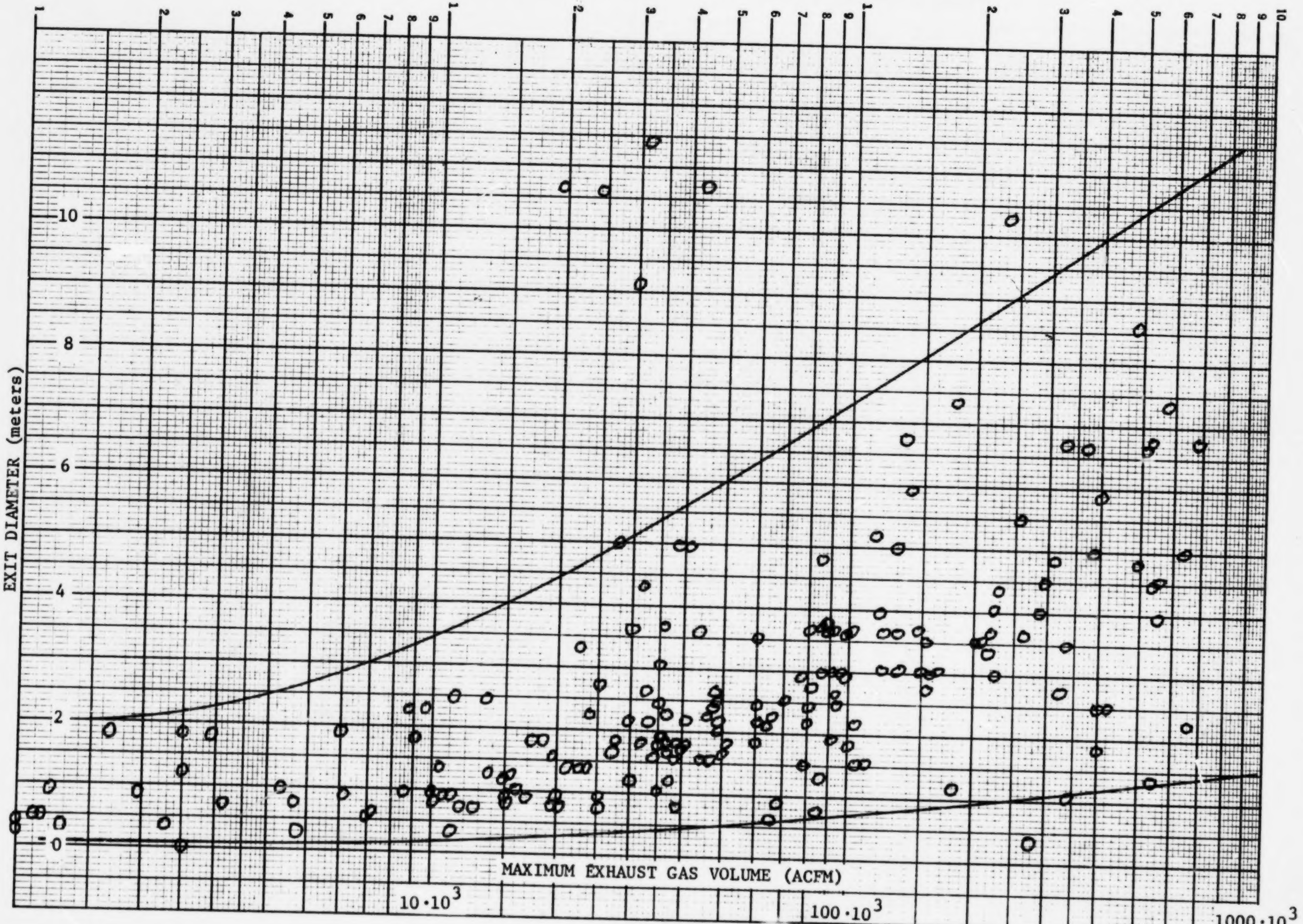

Figure C-14. Exit Diameter Range for Industrial Process Sources

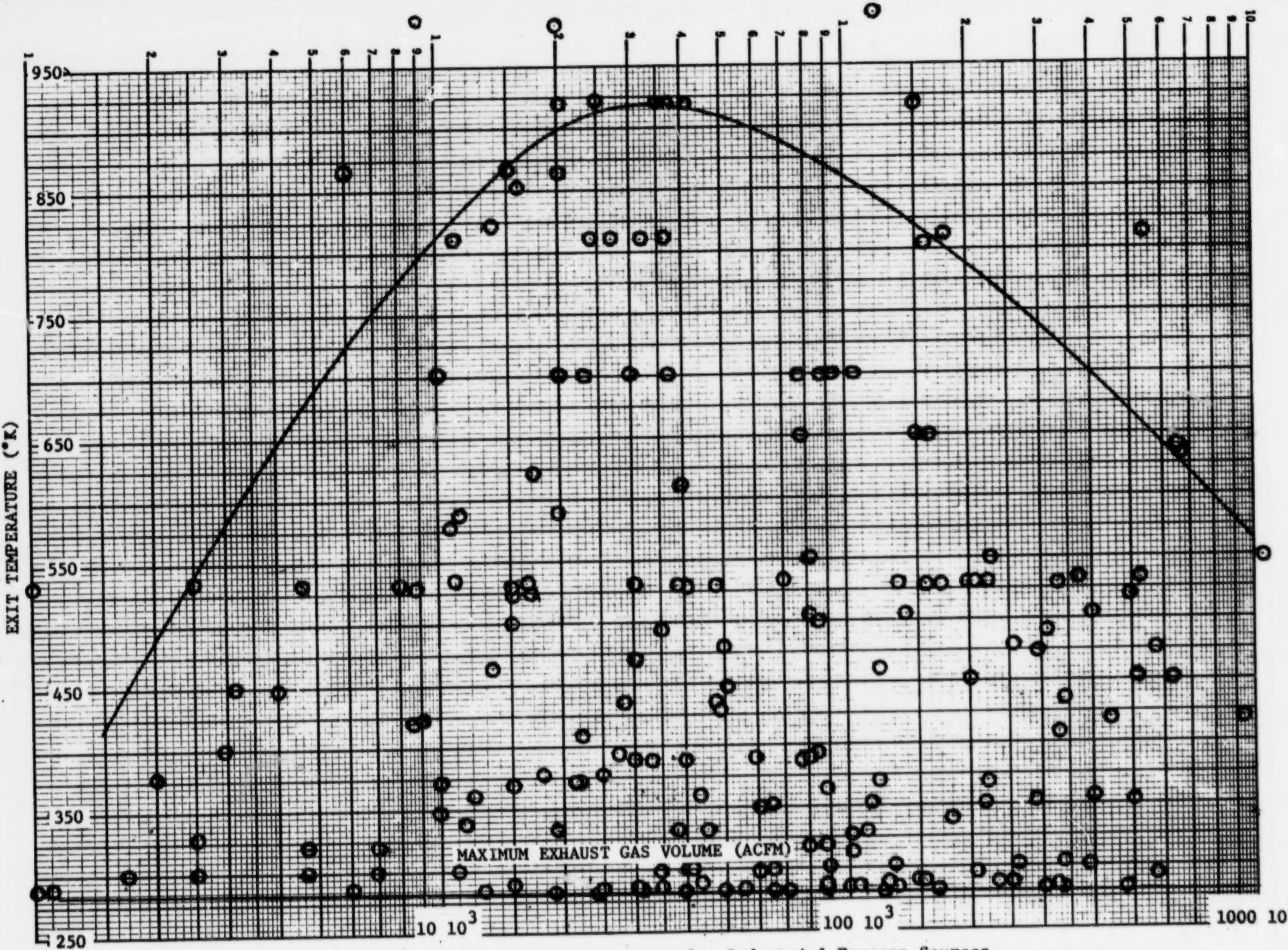

Figure C-15. Exit Temperature Range for Industrial Process Sources

Table C-2. Effective Stack Height Diameter Range

		Plant Size			
		Small	Medium	Large	Extra-Large
Rated Capacity (BTU/hr)[1]		50E6	400E6	1500E6	6000E6
ACFM[1]		20E3	150E3	600E3	2000E3
h (meters)	PP[2]	--	35-96(64)[3]	46-118(83)	76-162(122)
	FC	9-94(41)	17-84(47)	26- 77(51)	37- 70(55)
	IP	5-70(18)	8-95(35)	10-130(65)	12-130(91)
V (meters/sec.)	PP	--	1-22(7)	2- 34(12)	4-46(22)
	FC	.1-15(5)	.1-19(9.5)	6- 21(13.5)	13-23(175)
	IP	.5-21(6)	.5-25(6)	.5- 26(6)	.5-27(6)
D (meters)	PP	--	.5-5.5(3.5)	2.-6.5(4)	3-8(5.5)
	FC	.5-3.5(2)	.5-5 (2.5)	.5-6 (3)	1-7(3.5)
	IP	.5-4.5(2)	1-8 (4.5)	1.5-10.5(6)	2-12(7.5)
T (deg kelvin)	PP	--	400-525(465)	390-480(440)	385-465(425)
	FC	460-590(525)	425-545(485)	400-520(460)	380-490(435)
	IP	280-925(500)	280 (425)	280 (375)	280-525(300)

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[1] Defines plant size.

[2] PP = Power Plant, FC = non-Power Plant Fuel Combustion, IP = Industrial Process

[3] XX-XX(XX) = range (nominal).